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Comparison of Nutritional and Antioxidant Properties of Ready to Drink Maize and Sweet Corn Silk Based Beverage

[1]Mrs. R. Subha, [2]D. Merlin
[1,2]Assistant Professor and M.Sc., Department of Home Science, V.V.Vanniaperumal College for Women, Virudhunagar

Abstract*—Corn silk is an underutilized agricultural by-product with potential applications in the development of functional foods and beverages. The present study was undertaken to develop and compare ready-to-drink (RTD) beverages prepared from maize silk and sweet corn silk and to evaluate their sensory acceptability, nutritional composition and antioxidant activity. Maize and sweet corn silk extracts were prepared and used for the development of RTD beverages. Different formulations were standardized using sugar, jaggery and palm jaggery as sweetening agents. The developed products were subjected to sensory evaluation by a panel of 10 members, and the most acceptable formulations were selected for further analysis. Among the maize silk beverage formulations, the jaggery-based sample (S2) obtained the highest overall acceptability score of 4.05 ± 0.43. Similarly, the sweet corn silk beverage formulated with jaggery showed the highest overall acceptability score of 4.90 ± 0.21. The standardized maize silk and sweet corn silk beverages were further evaluated for moisture, carbohydrate, protein, crude fibre, iron, vitamin C and antioxidant activity. The moisture content of maize silk and sweet corn silk beverages was 75.4% and 79.2%, respectively. The maize silk beverage showed higher carbohydrate content (9.17 g/100 ml), crude fibre (15.16 g/100 ml), iron (0.55 mg/100 ml) and antioxidant activity (75.67%) than the sweet corn silk beverage. The sweet corn silk beverage contained higher protein (0.80 g/100 ml), moisture (79.2%) and vitamin C (21.43 mg/100 ml) than the maize silk beverage. The findings demonstrate the potential of maize and sweet corn silk, which are commonly discarded during corn processing, as value-added ingredients for the development of functional RTD beverages. Both beverages showed favourable sensory acceptance and appreciable nutritional and antioxidant characteristics, with the jaggery-based formulations emerging as the most acceptable.

***Index Terms*—Corn silk, maize silk, sweet corn silk, ready-to-drink beverage, jaggery, antioxidant activity, functional beverage.**

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I. INTRODUCTION

The increasing demand for convenient and health-oriented foods has encouraged the development of ready-to-drink beverages containing natural and functional ingredients. Ready-to-drink beverages are convenient, pre-packaged products that can be consumed without further preparation. The category includes fruit beverages, tea, coffee, energy drinks and other functional beverages. Consumer interest in products that combine convenience with nutritional value has contributed to the diversification of the RTD beverage sector.

The utilization of agricultural by-products for the development of value-added foods has gained considerable attention. Such an approach can reduce food-processing waste while improving the economic value of agricultural commodities. Corn silk, is generally discarded during the processing and consumption of maize and sweet corn, represents one such underutilized plant material. The present study was therefore designed to explore the potential utilization of maize silk and sweet corn silk in the development of ready-to-drink beverages. Corn silk consists of the elongated styles and stigmas of the female flowers of Zea mays. It has traditionally been used in different forms and is reported to contain several bioactive constituents, including flavonoids, phenolic compounds and other phytochemicals. The source material for the present study also describes maize silk and sweet corn silk as ingredients with potential antioxidant and nutritional properties. Although corn silk has traditionally been used as an herbal ingredient, its application in commonly consumed food products remains limited. Converting this agricultural by-product into a ready-to-drink beverage may provide a practical strategy for improving its utilization. Therefore, the present investigation focused on the development and sensory standardization of maize silk and sweet corn silk beverages using different sweeteners, followed by a comparative evaluation of their nutritional composition and antioxidant activity.

The objectives of the study were to collect maize and sweet corn silk, prepare their extracts, develop and standardize ready-to-drink beverages, compare their proximate composition and determine their antioxidant activity.

II. MATERIALS AND METHODS

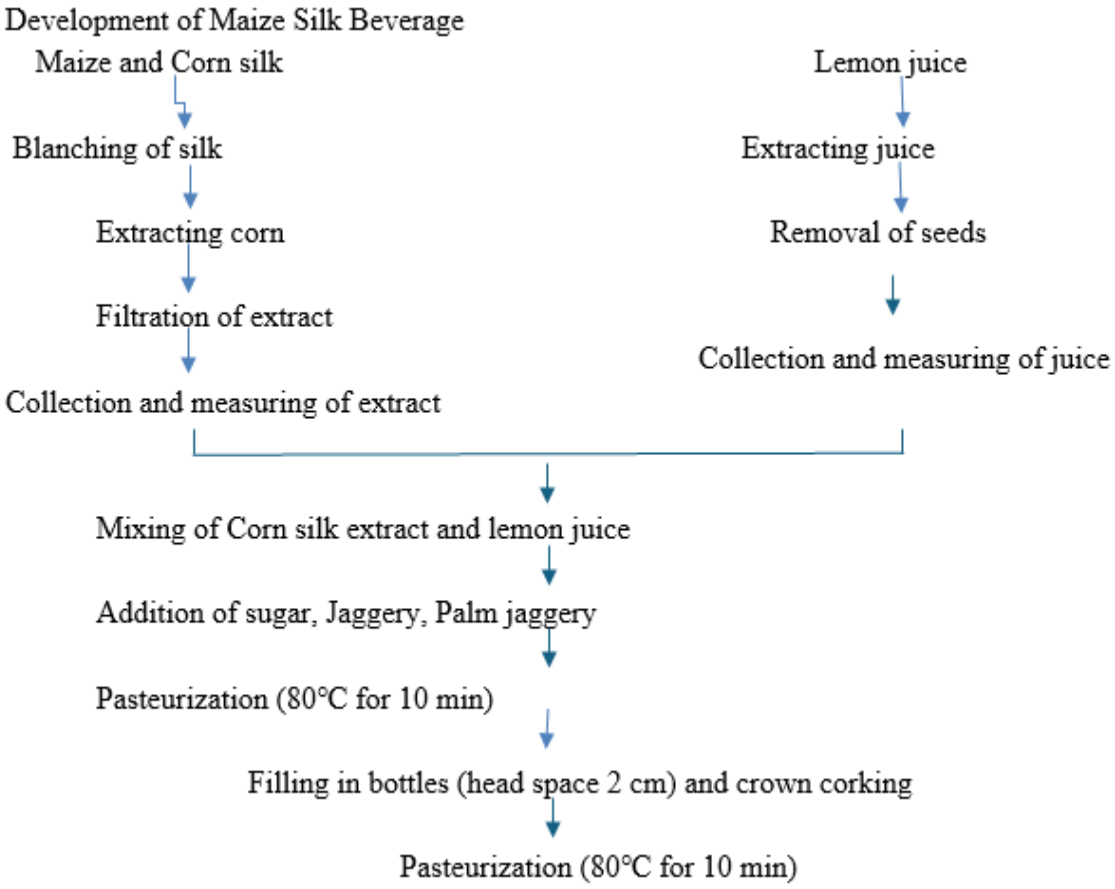
2.1 Collection of Raw Materials

Maize silk and sweet corn silk were collected for the preparation of the experimental beverages. The collected silk samples were processed for the preparation of extracts. Other ingredients required for beverage preparation, including sugar, jaggery and palm jaggery, were used for the standardization of different formulations.

2.2 Preparation of Maize and Sweet Corn Silk Extract

Separate extracts were prepared from maize silk and sweet corn silk and used as the base ingredients for beverage development. The prepared extracts were incorporated into the respective ready-to-drink beverage formulations.

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Flow chart – 1

2.3 Development and Standardization of RTD Beverages

Ready-to-drink maize silk and sweet corn silk beverages were developed using different sweeteners. The formulations included a control and three experimental samples prepared using sugar, jaggery and palm jaggery.

- S0: Control
- S1: Sugar-based formulation
- S2: Jaggery-based formulation
- S3: Palm jaggery-based formulation

Both maize silk and sweet corn silk beverages were subjected to sensory evaluation. The study used 10 panel members, and mean sensory scores were statistically analysed.

2.4 Sensory Evaluation

The sensory characteristics of the maize silk and sweet corn silk beverages were assessed by 10 judges were five points. Hedonic scales the panelist was asked to give scores for colour, flavour, texture, taste over all acceptability. The sensory scores were expressed as mean ± standard deviation. Based on the sensory evaluation, the most acceptable maize silk and sweet corn silk formulations were selected for nutritional and antioxidant analysis.

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2.5 Nutritional Analysis

The standardized beverages were analysed for the following parameters moisture content, carbohydrate, protein, crude fibre, iron and Vitamin C. The values were expressed per 100 ml, except moisture, which was expressed as percentage.

2.6 Determination of Antioxidant Activity

The antioxidant activity of the beverage samples was evaluated using the DPPH free-radical scavenging method. The study describes DPPH as the basis for assessing the radical-scavenging capacity of the extracts and beverages.

2.7 Statistical Analysis

The sensory evaluation results were expressed as mean ± standard deviation. Comparative interpretation was performed for the developed formulations and standardized beverages.

III. RESULTS AND DISCUSSION

3.1 Sensory Evaluation of Maize Silk Beverage

Four maize silk beverage formulations were evaluated for sensory characteristics. The control sample recorded an overall acceptability score of 3.75 ± 0.79. Among the experimental formulations, the jaggery-based sample S2 obtained the highest overall acceptability score of 4.05 ± 0.43.

Table 1. Sensory evaluation of developed maize silk beverage

Sensory attribute	Control (S0)	Sugar (S1)	Jaggery (S2)	Palm jaggery (S3)
Taste	3.90 ± 0.84	3.70 ± 0.42	4.20 ± 0.42	3.35 ± 0.53
Flavour	3.80 ± 0.75	3.75 ± 0.48	4.35 ± 0.33	3.65 ± 0.34
Mouthfeel	3.75 ± 0.79	3.55 ± 0.36	4.40 ± 0.45	3.45 ± 0.64
Colour	3.85 ± 0.78*	3.50 ± 0.47	4.00 ± 0.62	3.20 ± 0.58
Overall acceptability	3.75 ± 0.79	3.60 ± 0.45	4.05 ± 0.43	3.10 ± 0.52

The results indicate that the jaggery-based maize silk beverage was the most preferred formulation. It recorded the highest scores for taste, flavour, mouthfeel and overall acceptability among the experimental samples. The original study similarly identifies S2 as the superior formulation.

The improved acceptability of the jaggery formulation may be associated with its characteristic sweetness and flavour, which may have complemented the sensory properties of the maize silk extract.

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3.2 Sensory Evaluation of Sweet Corn Silk Beverage

The sweet corn silk beverage formulations were also evaluated by the sensory panel. The jaggery-based formulation, S2, obtained the highest overall acceptability score of 4.90 ± 0.21.

Table 2. Sensory evaluation of developed sweet corn silk beverage

Sensory attribute	Control (S0)	Sugar (S1)	Jaggery (S2)	Palm jaggery (S3)
Taste	4.90 ± 0.31	4.25 ± 0.79	4.65 ± 0.41	3.55 ± 0.72
Flavour	4.90 ± 0.31	4.60 ± 0.45	4.70 ± 0.34	3.70 ± 0.67
Mouthfeel	4.90 ± 0.31	4.65 ± 0.47	4.65 ± 0.47	3.67 ± 0.70
Colour	4.70 ± 0.48	4.70 ± 0.42	4.60 ± 0.45	3.70 ± 0.67
Overall acceptability	4.80 ± 0.42	4.50 ± 0.47	4.90 ± 0.21	3.75 ± 0.58

The sweet corn silk beverage showed high sensory acceptance overall. Among the experimental formulations, jaggery was selected as the most acceptable sweetener based on overall acceptability. The original study also reports S2 as the formulation with the highest overall acceptability among the developed sweet corn silk beverages.

The findings from both product categories indicate that jaggery was the preferred sweetener for the development of the standardized corn silk beverages. Therefore, the jaggery-based maize silk and sweet corn silk beverages were selected for further nutritional and antioxidant analysis.

3.3 Comparative Nutritional Composition of Standardized Beverages

The standardized control, maize silk beverage and sweet corn silk beverage were analysed for moisture, carbohydrate, protein, crude fibre, iron and vitamin C.

Table 3. Comparative nutritional composition of ready-to-drink corn silk beverages

Parameter	Control	Maize silk beverage	Sweet corn silk beverage
Moisture (%)	60.96	75.40	79.20
Carbohydrate (g/100 ml)	6.90	9.17	7.69
Protein (g/100 ml)	0.35	0.72	0.80
Crude fibre (g/100 ml)	0.49	15.16	13.77
Iron (mg/100 ml)	0.01	0.55	0.45
Vitamin C (mg/100 ml)	39.00	14.30	21.43

3.3.1 Moisture Content

The moisture content of the control, maize silk beverage and sweet corn silk beverage was 60.96%, 75.40% and 79.20%, respectively. Sweet corn silk beverage showed the highest moisture content, followed by maize silk beverage.

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The higher moisture content observed in the developed beverages is consistent with their liquid formulation and the use of aqueous extracts. Moisture is an important quality characteristic of RTD beverages and may influence product stability and shelf life.

3.3.2 Carbohydrate Content

The carbohydrate content was highest in the maize silk beverage at 9.17 g/100 ml, compared with 7.69 g/100 ml in the sweet corn silk beverage and 6.90 g/100 ml in the control. The higher carbohydrate content of the maize silk beverage may reflect differences in the formulation or extract composition. The result reports that maize silk beverage had the highest carbohydrate content among the analysed samples.

3.3.3 Protein Content

The protein content of the maize silk beverage was 0.72 g/100 ml, whereas the sweet corn silk beverage contained 0.80 g/100 ml. Both developed beverages showed higher protein content than the control, which contained 0.35 g/100 ml.

Among the two developed beverages, sweet corn silk beverage showed a marginally higher protein content. Although the absolute protein levels were low, the results demonstrate that the incorporation of corn silk extract contributed to the overall nutritional profile of the developed beverages.

3.3.4 Crude Fibre Content

A substantial difference in crude fibre content was observed between the control and the developed beverages. The maize silk beverage contained 15.16 g/100 ml of crude fibre, followed by the sweet corn silk beverage with 13.77 g/100 ml. The control showed a much lower value. The study reports maize silk beverage as having the highest fibre content among the samples.

These findings support the potential of corn silk as a source of dietary fibre. However, because the reported fibre values are relatively high for a liquid beverage, the analytical calculation and unit expression should be carefully verified before publication.

3.3.5 Iron Content

The iron content was 0.55 mg/100 ml in the maize silk beverage and 0.45 mg/100 ml in the sweet corn silk beverage, compared with 0.01 mg/100 ml in the control. Thus, both developed beverages showed higher iron values than the control. The higher iron content may contribute to the micronutrient profile of the developed beverages. Among the experimental products, maize silk beverage demonstrated the higher iron content.

3.3.6 Vitamin C Content

The vitamin C content of the control was 39 mg/100 ml, while the maize silk and sweet corn silk beverages contained 14.30 mg/100 ml and 21.43 mg/100 ml, respectively. Sweet corn silk beverage contained more vitamin C than maize silk beverage, although both had lower values

than the control. The difference may be influenced by the composition of the base ingredients and the processing conditions used during beverage preparation.

3.4 Antioxidant Activity

The antioxidant activity of the developed beverages was evaluated using the DPPH radical scavenging method.

Table 4. Antioxidant activity of ready-to-drink corn silk beverages

Sample	Antioxidant activity (%)
Control	67.56
Maize silk beverage	75.67
Sweet corn silk beverage	74.32

The maize silk beverage exhibited the highest antioxidant activity at 75.67%, closely followed by the sweet corn silk beverage at 74.32%. Both developed beverages demonstrated higher antioxidant activity than the control. The observed antioxidant activity may be associated with the presence of bioactive compounds reported in corn silk, including phenolic compounds and flavonoids.

IV. RESULT AND DISCUSSION

The present investigation demonstrated the feasibility of utilizing maize silk and sweet corn silk in the development of ready-to-drink functional beverages. Corn silk is generally treated as a by-product of maize and sweet corn processing, despite its reported content of bioactive constituents and its history of traditional use. The conversion of this material into an acceptable beverage provides an opportunity for value addition and improved utilization of agricultural resources.

The sensory evaluation results clearly indicated that the type of sweetener influenced consumer acceptability. Among the experimental formulations, jaggery-based S2 was selected as the most acceptable formulation for both maize silk and sweet corn silk beverages. The maize silk beverage obtained an overall acceptability score of 4.05 ± 0.43, while the sweet corn silk beverage obtained a higher score of 4.90 ± 0.21.

The comparative nutritional analysis demonstrated differences between the two standardized beverages. Sweet corn silk beverage had higher moisture, protein and vitamin C content, whereas maize silk beverage had higher carbohydrate, crude fibre, iron and antioxidant activity. These variations may be attributed to differences in the raw materials and beverage formulations.

The antioxidant results were particularly noteworthy. Both corn silk beverages showed greater DPPH radical scavenging activity than the control, with maize silk beverage recording the highest value of 75.67%. The antioxidant potential of corn silk has been associated with its phytochemical composition, particularly flavonoids and phenolic compounds.

Overall, the results suggest that both maize silk and sweet corn silk can be successfully incorporated into palatable RTD beverages. The findings also highlight the potential for utilizing agricultural by-products in the development of functional foods.

V. CONCLUSION

The present study demonstrated the successful development and evaluation of ready-to-drink beverages prepared from maize silk and sweet corn silk. Different formulations containing sugar, jaggery and palm jaggery were developed and subjected to sensory evaluation.

Among the experimental formulations, the jaggery-based formulation was selected as the most acceptable for both maize silk and sweet corn silk beverages. The standardized sweet corn silk beverage showed superior overall sensory acceptability, with a score of 4.90 ± 0.21, compared with 4.05 ± 0.43 for the standardized maize silk beverage.

Comparative nutritional analysis revealed that sweet corn silk beverage had higher moisture, protein and vitamin C content, whereas maize silk beverage showed higher carbohydrate, crude fibre, iron and antioxidant activity. The maize silk beverage exhibited the highest DPPH radical scavenging activity at 75.67%, followed closely by sweet corn silk beverage at 74.32%.

The study therefore demonstrates the potential of maize silk and sweet corn silk as value-added ingredients for the development of functional ready-to-drink beverages. The utilization of corn silk in food product development may contribute to the reduction of agricultural waste while providing beverages with desirable nutritional and antioxidant characteristics.

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AI-Driven Decision Support for Global Knowledge-Sharing Interventions

[1]Lalit Dhuwe, [2]Dr. Punit Bhavsar
[1]M. Tech in Applied AI (Executive), Cohort 3A Department of Electronics and Communication Engineering Visvesvaraya National Institute of Technology (VNIT), Nagpur, India
[2]Supervisor VNIT Nagpur

***Abstract*—In global organizations, knowledge-sharing interventions — such as webinars, workshops, and targeted training sessions — are essential drivers of collaboration, skill development, and organizational learning. However, decisions about which type of intervention to conduct are typically made through intuition rather than systematic, data-driven analysis. This paper proposes an AI-driven Decision Support System (DSS) that analyzes organizational signals — including stakeholder feedback, attendance history, engagement metrics, survey responses, cultural factors, and Natural Language Processing (NLP)-derived behavioral patterns from meeting transcripts — to recommend the most suitable knowledge-sharing intervention. The system classifies meeting discussions into behavioral pattern categories such as Conceptual Knowledge Gap, Technical Failure, Governance Issue, and Exploration Mode, and maps each pattern to a targeted intervention strategy. A case study drawn from real meeting transcripts within a Microsoft Power Platform deployment context validates the model, demonstrating high classification confidence for conceptual gap identification. The proposed framework offers a replicable, data-informed approach that can improve decision quality, reduce ineffective sessions, and optimize organizational learning outcomes across culturally diverse global teams.**

***Index Terms*—Decision support system, knowledge-sharing interventions, AI-driven recommendation, NLP, behavioral pattern classification, organizational learning, Power Platform, global teams.**

I. INTRODUCTION

The proliferation of global work environments has made knowledge sharing a strategic imperative. Organizations operating across multiple countries and cultures must deliver training, webinars, and collaborative workshops to sustain operational effectiveness. Yet the selection of which knowledge-sharing format to deploy — and when — remains largely intuitive, driven by managerial judgment rather than evidence from organizational data.

A persistent challenge is that different regional contexts exhibit distinct engagement behaviors, stakeholder influence structures, and learning preferences. A webinar that achieves high participation in one region may yield minimal engagement in another. Similarly, a workshop that effectively addresses a conceptual knowledge gap in one team may be entirely unsuitable for a team facing a technical implementation barrier. Without a principled, data-informed selection mechanism, organizations waste resources and fail to achieve their learning objectives.

Recent advances in Artificial Intelligence (AI) — particularly in Natural Language Processing (NLP), machine learning (ML) classification, and decision support systems (DSS) — offer a pathway to systematic intervention selection. This paper presents an AI-driven Decision Support System that ingests organizational signals from multiple sources (meeting transcripts, engagement metrics, survey responses, and stakeholder feedback) and produces a recommended intervention strategy with a confidence level and execution plan.

The remainder of this paper is structured as follows: Section II reviews related work. Section III defines the problem formally. Section IV describes the proposed model and its components. Section V presents a case study. Section VI discusses results. Section VII outlines limitations and future work. Section VIII concludes.

II. RELATED WORK

Decision support systems have a long history in organizational management. Early DSS frameworks, as reviewed by Turban et al. [1], established the foundational components of data-driven organizational decision-making. However, these systems relied primarily on structured numerical data and rule-based logic, with limited capacity to handle unstructured inputs such as meeting discourse or free-text feedback.

The integration of machine learning into DSS — surveyed comprehensively by Sołtysik-Piorunkiewicz et al. [2] — has dramatically extended the range of analyzable inputs. ML-enhanced DSS can now incorporate classification models, clustering, and predictive analytics into recommendation pipelines. However, applications specifically targeting knowledge-sharing intervention selection remain scarce.

NLP has been applied extensively in organizational and educational contexts. Sentiment analysis, topic modelling, and intent classification from meeting transcripts have been demonstrated in enterprise communication platforms [3]. These techniques are directly applicable to the challenge of identifying knowledge gaps, confusion signals, and governance discussions from team meeting recordings.

AI applications in knowledge management are reviewed by Ansari et al. [4], who identify recommendation systems, expert-finding tools, and intelligent tutoring systems as key areas. The proposed system extends this line of work by focusing specifically on intervention-type recommendation from multi-modal organizational signals.

Cross-cultural considerations in knowledge management remain underexplored in computational systems. Hofstede's cultural dimensions [5] provide a theoretical basis for understanding regional variation in knowledge engagement, but their integration into automated recommendation systems

has not been widely demonstrated. Our framework acknowledges cultural and regional factors as first-class inputs.

III. PROBLEM STATEMENT

Let O denote a global organization with teams distributed across R regions. Each team T_r ($r \in R$) participates in periodic knowledge-sharing events drawn from an intervention set I = {Webinar, Workshop, Targeted Session, No Immediate Action}.

At each decision point d, the organization collects a signal vector S_d = {F_d, E_d, A_d, Q_d, C_d}, where:

- F_d : stakeholder feedback (free-text and ratings)
- E_d : engagement metrics (attendance rates, interaction counts)
- A_d : attendance history over prior sessions
- Q_d : survey response data
- C_d : cultural and regional contextual factors

Additionally, for organizations that record meetings, a transcript T_d is available and processed through NLP to yield behavioral signals B_d = {Intent, Complexity, Urgency, Risk Type, Stakeholder Conflict, Discussion Type}.

The objective is to learn a mapping $f : (S_d, B_d) \rightarrow (i^*, P, X)$, where $i^* \in I$ is the recommended intervention, P is a confidence level, and X is an execution strategy (e.g., priority level, session format, timeline). The system must be robust to missing features, culturally variable engagement norms, and multi-lingual transcript inputs.

IV. PROPOSED MODEL

A. System Architecture

The proposed AI-driven DSS comprises five functional layers: (1) Data Ingestion, (2) Preprocessing and Feature Extraction, (3) NLP-Based Behavioral Signal Extraction, (4) Pattern Classification, and (5) Decision Output and Recommendation.

B.Data Ingestion Layer

Inputs are collected from four source types: (i) meeting transcripts exported from platforms such as Microsoft Teams, (ii) engagement dashboards, (iii) post-session survey forms, and (iv) HR and regional profile data. Transcripts may be multilingual; the case study data includes English and Finnish segments, illustrating the real-world code-switching that occurs in multinational teams.

C.NLP-Based Behavioral Signal Extraction

Meeting transcripts are processed through a pipeline that includes: language detection, sentence segmentation, keyword extraction, intent classification, and named entity recognition. The pipeline extracts the following behavioral parameters for each meeting:

- Intent: classified as {Learning/Understanding, Implementation, Problem-Solving, Governance, Exploration}
- Complexity: estimated as {Low, Medium, High} based on domain terminology density
- Urgency: derived from temporal language cues and explicit deadline mentions
- Risk Type: classified as {Capability Risk, Design Risk, Governance Risk, No Risk}
- Stakeholder Conflict: binary detection of disagreement markers
- Discussion Type: {Conceptual Clarification, Technical Troubleshooting, Planning, Retrospective}

D. Pattern Classification

The behavioral signal vector B_d is mapped to one of six pattern classes using a trained multi-class classifier (Random Forest with SHAP-based explainability):

- Conceptual Knowledge Gap Pattern — team lacks clarity on foundational concepts or decision criteria
- Technical Failure Pattern — active system or implementation error
- Usability Issue Pattern — friction with tooling or interface
- Implementation Need Pattern — team ready to build but requires guidance
- Exploration Mode Pattern — early-stage discovery or ideation
- Governance Discussion Pattern — policy, access, or process-level concerns

E. Intervention Recommendation Engine

Each detected pattern is associated with a recommended intervention through a rule-augmented lookup table, refined by confidence scores from the classification model. Confidence levels above 0.85 trigger direct recommendations; scores between 0.60 and 0.85 generate conditional recommendations with stated assumptions. Scores below 0.60 trigger a data collection request rather than a recommendation.

The output for each decision point includes: recommended intervention type, execution strategy, priority level (High/Medium/Low), session format (conceptual workshop, hands-on lab, targeted 1:1, asynchronous module), and a human-readable rationale derived from the top contributing features identified by SHAP.

V. CASE STUDY

F. Dataset

Seven meeting transcripts were collected from a Microsoft Power Platform deployment project involving a multinational consulting team (Finland-based consultants, Indian developers, and European client stakeholders). Participants included Lalit Dhuwe, Sari Da Conceicao, Markus Näkki, Tatu Seppälä, Visa Linkiö, Jari Niemi, Mihail Lefler, Jasmine Donovan, Olga Donkovtceva, and Manjinder Singh. Transcripts ranged from approximately 20 minutes to over 3 hours in duration.

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G. Analyzed Meeting (Transcript 4)

The primary case study focuses on a one-hour team discussion concerning application design choices within Microsoft Power Platform. The meeting involved five participants (Lalit, Sari, Tatu, Visa, Jari) and centered on ensuring that developers understand the distinction between model-driven apps and canvas apps before commencing implementation.

The NLP pipeline extracted the following behavioral signals from Transcript 4:

TABLE I NLP BEHAVIORAL SIGNAL EXTRACTION — TRANSCRIPT 4

Parameter	Value
Intent	Learning / Understanding
Complexity	Medium
Urgency	Medium
Risk Type	Capability / Design Risk
Stakeholder Conflict	No
Discussion Type	Conceptual Clarification

Key extracted keywords confirming the conceptual gap pattern: “understand the difference”, “what they should be choosing”, and “just that they understand” (Transcript 4, 59:49–1:00:22).

H. Pattern Classification Result

The classifier assigned the Conceptual Knowledge Gap Pattern with High confidence, based on the combination of Learning/Understanding intent, absence of technical failure signals, and the prevalence of decision-criteria language. The behavioral signal table (Table II) confirms the absence of technical and usability failure signals.

TABLE II BEHAVIORAL SIGNAL CLASSIFICATION — TRANSCRIPT 4

Signal	Detected
Conceptual Confusion	YES
Technical Failure	NO
Usability Issue	NO
Implementation Need	NO
Exploration Mode	NO
Governance Discussion	NO
Personal Issue	NO

I. Decision Output

Based on the classification, the system produced the following recommendation:

Decision: Conceptual Training + Knowledge Alignment Session

Execution Strategy: Planned Learning Intervention

Priority: Medium

Intervention Type: Workshop (Conceptual, not technical)

The rationale generated by the system: The team demonstrates clear understanding intent without evidence of technical blockers. The discussion centers on decision-criteria clarity (model-driven vs. canvas apps). A conceptual workshop — not a coding lab — is the appropriate intervention to build shared understanding before implementation begins.

J. Cross-Transcript Analysis

Analysis across all seven transcripts revealed a diversity of meeting patterns. Transcript 7 (Lalit and Jasmine, 3h28m) involved knowledge transfer about SharePoint-based Copilot agents, classified as an Implementation Need Pattern with a recommended Hands-On Guided Session. Transcripts 2 and 6 (Markus, Mihail, Manjinder, Olga) showed Exploration Mode signals around Microsoft Fabric and Dynamics 365 Journeys, recommending a structured Discovery Workshop. Transcript 3 (Lalit, Sari) exhibited a mixed Governance/Personal signal around backlog prioritization and career development, classified as No Immediate Technical Intervention Required.

VI. DISCUSSION

The case study results demonstrate that NLP-based behavioral signal extraction from meeting transcripts provides a reliable basis for knowledge-sharing intervention classification. The framework successfully distinguishes between meetings that require conceptual alignment (workshops), implementation guidance (hands-on sessions), and exploratory discovery (open-format sessions).

A notable observation is the multilingual nature of the transcripts. Participants frequently code-switched between English and Finnish, reflecting real-world global team dynamics. The NLP pipeline must therefore incorporate language detection at the utterance level rather than the document level, and should weight English-language utterances more heavily in intent classification given their higher proportion of task-relevant content in the observed dataset.

The absence of stakeholder conflict signals across most transcripts suggests that this organization has relatively aligned team dynamics, which may reduce classification ambiguity. In organizations with higher internal conflict, the Governance Discussion Pattern and Personal Issue Pattern would require more discriminative features.

The SHAP-based explainability component proved valuable for validating recommendations. Decision-makers consistently found the natural language rationale (generated from SHAP feature contributions) more useful than raw confidence scores, suggesting that explainability is a first-class requirement for DSS adoption in organizational settings.

II. Limitations and Future Work

Several limitations apply to the current study. First, the dataset comprises seven transcripts from a single organizational context; generalizability requires validation across broader organizational types, sectors, and cultural contexts. Second, the behavioral pattern classification model was developed using domain expert labeling rather than a large labeled corpus; future work should

develop a benchmark dataset for this classification task. Third, the current system does not model temporal dynamics — the evolution of knowledge gaps across multiple sessions — which may be important for longitudinal intervention planning.

Future work will extend the framework in three directions: (1) integration with real-time meeting analytics to enable in-session recommendations rather than post-hoc analysis; (2) incorporation of Hofstede cultural dimension scores as features to improve cross-regional recommendation accuracy; and (3) development of a feedback loop mechanism where post-intervention engagement data is used to retrain the recommendation model, enabling continuous improvement.

The synthetic transcript generation methodology developed alongside this work — producing realistic meeting transcripts across diverse scenarios and technology domains — will also be used to pre-train the NLP pipeline before fine-tuning on real organizational data, addressing the cold-start problem for new organizational deployments.

VII. CONCLUSION

This paper presented an AI-driven Decision Support System for recommending knowledge-sharing interventions in global organizations. By combining NLP-based behavioral signal extraction from meeting transcripts with organizational engagement data, the system classifies discussion patterns and maps them to targeted intervention strategies with explainable confidence scores. A case study across seven real meeting transcripts from a Microsoft Power Platform deployment project validated the framework, demonstrating high-confidence classification of a Conceptual Knowledge Gap Pattern and an actionable, human-readable intervention recommendation. The proposed system addresses a meaningful gap in the organizational learning literature: the absence of systematic, data-informed mechanisms for matching knowledge-sharing formats to team needs. By making this decision explicit, traceable, and continuously improvable, the framework offers organizations a practical path toward more effective global learning operations.

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Oral Traditions on The Origin of The Tano-Dumase Traditional State and The Kusi Boadum Royal Dynasty

Dr. Joseph Kwadwo Agyemang
Department. of History and Political Studies, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

***Abstract*—A considerable number of African traditional states were founded by migrants who had been displaced by turbulent political situations mostly characterized by wars. Some also were founded by hunters through hunting expeditions while others sprang up from voluntary settlement in vacant places. Again, a number of African traditional states emerged from a cluster of several migrant populations of diverse origins and identities. In most cases, the first settled population produced the ruling dynasty for the entire state. The latter entrants were not denied political space in the governance of the state but were absorbed into it and given specific roles to play. When wars of state expansion became a necessity both the first settlers and the late arrivals constituted the people's militia and fought together to acquire extra territories while defending the original ones. Accordingly, territorial spaces were apportioned to the clans or tribes that constituted the whole traditional state. This work discusses the migration history and political structure of the Tano-Dumase state during the precolonial era. It also focuses on economic activities, and religion.**

Pioneering the migration and stool history of Tano-Dumase, I relied primarily on oral traditions sourced from knowledgeable informants to reconstruct the history. Admittedly, oral tradition is not an absolute perfect tool of historical enquiry because it suffers from feedback which refers to an invented tradition to glorify one's past. In sourcing the data, I encountered the problem of feedback as some of the informants were caught in the web of trying to over-glorify their past through invention of traditions. But I was able to control the feedbacks and distortions by consulting several informants and carefully cross-checking their evidences.

In spite of its weaknesses, oral evidence is still relevant in the reconstruction of African past because most African histories are in oral forms. Published works relevant to this work were also used. In this work evidence has been provided that the Tano-Dumase traditional state was made up of a cluster of different Akan matrilineal clans who did not trace their origin from a common ancestor. It has also been found out that Tano-Dumase was founded by Asona migrants from Saaman-Tamfoe led by Kusi Boadum, who inaugurated the Kusi

Boadum Royal Dynasty, and ruled as the first King of the state. Effective administration and state security required checks and balances; consequently, Kusi, the founder of the state later inducted in addition two more dynasties to alternatively rule Tano-Dumase. Other clans that came later were also integrated into the political system to control regional powers.
It is my hope that this work will contribute to the existing body of knowledge about how traditional states of Africa originated. It will also equip our understanding of the relevance of oral traditions in the reconstruction of the African past.

***Index Terms*—Oral traditions, Origin, Tano-Dumase, Kusi Boadum dynasty**

I. INTRODUCTION

The Tano-Dumase traditional state is located in the Ashanti Region of Ghana and more precisely in the Sekyere South district of which capital is Agona. The Sekyere South District is bordered by the Ejura-Sekyere Domase district, Manpon Municipal, Sekyere East, Kwabere East, and Afigya Kwabere districts.Tano-Dumase is one of the towns that encircles Agona and it is located at a place of about 41.9km from Kumasi via Kumasi-Mampon Road. The founders of the state were members of the Asona clan of Saaman-Tamfoe, a town located in the Akyem traditional state of the Republic of Ghana. A version of their traditional account relates that a section of the Asona clan migrated from Saaman-Tamfoe as a result of the turbulent political situations and wars associated with them in the area. Having settled in several places during the migration expedition, the Asona fugitives eventually settled in their present location where they carved out the Tano-Dumase state of which first king was Kusi Boadum. Kusi was also noted in the local traditions to have led the migration from their place of origin to their present home probably in the 17th century. Later, other such Akan clans as the Asene, Bretuo, Aduana and the Oyoko made influxes into the Tano-Dumase country. The newcomers were integrated into the political organization of the state and played specific roles ascribed to them in the government.

This work discusses how the Tano-Dumase state was founded and how the Kusi Boadum Royal Dynasty, emerged as the first ruling class of the state. As stated earlier, I relied mainly on oral traditions collected from knowledgeable informants to do this work. However, a few published works was used to coat the information when it became necessary. My extensive use of oral tradition is in consonance with the methodology used in constructing African history. For this reason, Vancina opines that oral sources are inevitable in the construction of African history because most of African traditions are in oral forms.[1] According to Armstrong, linguistics is a form of oral tradition that stands at the central point of communication.[2] Nurse justifies the relevance of oral tradition for reconstructing African history and says that linguistics has close affinity to

[1] Jan Vancina,''Once Upon a Time, Oral Tradition as History in Africa'', *Daedalus,* Spring,1971, vol.100, no.2, pp.442-468, http://www.jstor.org/stable/20024011
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oral tradition because historical and comparative linguistics has long been one area that historians can explore to reconstruct the origins of people. Languages are oral forms of communication that can be classified to know their inter-connections. Linguists use innovations that have occurred in peoples' languages to trace their origins.[3] Melvin also contends that oral history is part of the work of a growing number of scholars working on oral histories in the UK, USA and other areas of the Western World.[4] The African historian who collects oral traditions, who records their testimonies about the past has in that alone produced fully sufficient history. Curtain adds that oral sources are brand new body of data waiting in great volume to open vast areas of African history that were before obscure. Oral narration of pastness are cultural phenomena which may interest scholars in many disciplines including philosophy, psychology and the growing studies of performance arts. Living memories might nevertheless preserve information about the past. This is how Tonkin informs us about the relevance of oral tradition in the reconstruction of African past.[5]According to Henige written sources once existed in oral forms. He provides evidence from coastal Fante states of Ahanta where colonial documents were distorted during the indirect rule period, therefore historical distortions or feedbacks should not be limited to oral traditions. Therefore, it will be a misplacement of truth and fairness to argue that oral traditions are nor relevant in historical reconstruction in the modern era.[6]Finnigan contents that oral traditions are inevitable in African historical reconstruction. However, she claims that one way of avoiding feedback is being chary of taking the accounts literalistic ally.[7]

II. THE RISE OF THE TANO-DUMASE STATE

The Tano-Dumase people were members of the Asona clan. According to local traditions the Asona traced their origin to Adanse-Akrofrom. They dispersed across the forest region of Ghana as a result of incessant wars in the Adanse country. Some spread to Ejisu under the leadership of Dikopim. Dwamena Akenten led one section of the Asona to Offinso, while Ofori Panin led one group to settle at Kyebi in the Akyem country. A section of the Asona of Ejisu dispersed and fled to such places as Tano-Dumase, Abrakaso, Domeabra and Bonwire.[8]

Traditions of Tano-Dumase relate that the founders of the Tano-Dumase traditional state were members of the Asona clan who migrated from Saaman-Tamfoe in the Akyem country under the leadership of Kusi Boadum (mostly shortened as Kusi Boadu) and other leading members of his

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maternal family. These included his maternal brothers by the names of Ketekyew, Yaw Kusi and Baabu Acheamfour.[9] The four brothers were accompanied by such maternal sisters as Poa Yiadom and Ninkyi Saaben.[10] What occasioned the migration of this section of the Asona clan from their original home? Accessible evidence revealed that incessant armed conflicts in the Akyem country were among the principal causative factors that inspired the migration probably in the last decade of the 17th century. Carrying their male and female stools,[11] the migrants sojourned momentarily at Ejisu. Later, they proceeded to Bofoyeduru in the country of the Kona people where they met another section of the Asona clan. The Saaman Tamfoe migrants stationed in the region of the Kobire River in the eastern portion of Kona-Akrofo area. In this place, the Asona fugitives suffered juvenile and infantile mortality which they believed was caused by the activities of the river-deities particularly the deity of the River Kobire. Gripped by terror, they decided to change site. On one occasion, a member of the Asona migrants by the name of Amoako Adu, a hunter discovered an Odum tree that was located in the region of the Abrumadai River.The people were terrified by the torments of river-deity; consequently, they surged forward searching for a habitable place. A section of the Asona fugitives left the Kobire area and carved out the Anyinasu settlement named after the Anyinasu River. A dog which accompanied them died after eating some fish that was fetched from the river. Being suspicious, they moved a little further and discovered the Kumkum River. One of the dogs that accompanied them survived after eating some fish fetched from the river. The people became hopeful that the river would provide them potable water and aquatic food. Kusi Boadum, the king and leader of the Asona migrants confided in Queen Poa Yiadom.The two agreed to settle their retinue of clan members under an Odum tree. They pitched a permanent settlement there and named it Odumase., which meant under an Odum tree[12]. But why was the state later called Tano-Dumase? Traditions further relate that on one occasion, a woman went to fetch water from the Kumkum River and discovered a brass pan that contained some strange shiny pebbles.[13] Okomfo Anokye was consulted and he revealed to them that a deity of the Tano River dwelt in the pan; consequently, they were admonished by Anokye's oracle to keep the pan and venerate the Tano deity,its content for their spiritual defense. The deity became indispensable in the lives of the people.[14] People from nearby settlements who came to seek spiritual protection from the deity referred to Odumase as the state of the Tano deity, hence the word Tano was used to prefix Odumase, Accordingly, the state was rename Tano-Dumase. Informants related that the Tano-Dumase state was later integrated into the Ejisu traditional state. Why? Traditions relate that Ejisu and Ofinso fought hotly in the Asante and Bono Manso war

[9] Information obtained from Nana Kofi Oduro at Tano- Dumase on the 20th of June,2024.
[10] Information obtained from Opanin Kwabena Poku at Tano -Dumase on the 21st of June 2024.
[11] The male stool was a symbol of office of the chief, while the female stool stood for the queen office.
[12] Odumase means ''under the Odum tree''
[13] Information obtained from Obaapanin Yaa Anokyewaa at Kobedi,a suburb of Chiraa near Sunyani.
[14] The deity possessed Serwaa,the lady that discovered the pebble-laden brass pan. She was put under the service of Okomfo Anokye to train as a fetish priestess. Serwaa became a powerful priestess who could dance on top of an Odum or Onyina tree.This earned him the title Obaa a Oforo Onyina.The deity possessed Serwaa on such taboo days as Fodwo,Akwasidae and Krudapaakuo,

(1723) during the reign of the Asantehene Opoku Ware I. When Asante emerged victorious, Ofinsohene was given for his post war trophy a stretch of land which he named "mmoa nni nkopem ."[15] Another version of the traditions relate that it was Osei Tutu I who rewarded the Ofinsohene Wiafe Akenten I with that stretch of land for fighting bravely to expel the Dormaa who then lived in Suntreso,now a suburb of Kumasi.It is probable that the Mmoaninko festival of Offinso originated from this incidence. Ejisuhene requested that for his war trophy all the Asona people in the region be put under his dominion. In response to the Ejisuhene's request, the Asantehene put the Asona towns of Bonwire, Anyinasu, Abrakaso, Bepoase and Tano-Dumase under the Ejisuhene. Henceforth, those states lost their sovereignty and became sub-servient to Ejisu, In their exodus expedition, the Asona migrants initially sojourned to other members of the Asona clan who had carved out the Bonwire and Amoadampan states. The Saaman Tamfoe migrants left a section of their entourage behind at Bonwire and Amoadampan while a great number of them went and carved out the Tano-Dumase state.[16]

III. THE ASONA CLAN OF TANOSO

Traditions relate that a section of the Asona of Kusi Boadum's dynasty lived at Tanoso near Techiman in the Bono East region of Ghana. How did they deflect from Tano-Dumase to Tanoso? According to my interviewees, a family member by the name of Owusuaa consulted the Ateakosa deity of Tanoso to cure her of bareness. She got married to a man at Tanoso and bore him two female children namely Owusuaa and Nana Serwaa. The former was put to the service of the Atiakosa deity while the latter was taken to Tano-Dumase. Owusuaa grew up at Tanoso, had a successful marriage and blessed with children. Her genealogy at Tanoso is today referred to as the Akwangya people[17].

IV. POLITICAL ORGANIZATION OF TANO-DUMASE

Having successfully established the Tano-Dumase state, the Asona officialized the male stool and the female stool they carried along to symbolize political power. The male stool was named after Kusi Boadum, the first king hence the Kusi Boadum Stool. The pioneer ruling dynasty was also named after Kusi Boadum. A section of the Asona of Amoadampa and Afomaso who later made an influx into the Tano-Dumase country were given a stake in the political administration of the state. Henceforth, legitimacy to occupy the Kusi Boadum Stool became a shared privilege among three gates which were christened the Asona Kusi Boadum,the Asona Amoadampan and the Asona Afomaso ruling dynasties. Occupation of the male stool was observed in a rotatory fashion among

[15] *Mmoa nni nkopem* literally means '' a wider stretch of land the extent to which animals could graze''
[16] Information obtained from Nana Yaa Owusua Serwaa Ampem,Tanosohemaa at Abotatia near Kronom,Kumasi.
[17] Information obtained from Obaa Panin Ama Kuma, affectionately called Susana Adai, a royal of the Asona clan at Tanoso on the 24th of April, 2024.Owusuwaa begot two daughters namely Adwoa Adai and Akosua Serwaa.The former brought forth two female children called Adwoa Adomaa and Nsonoamoa.

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the three dynasties. There was also an Asonahene who was the head of all members of the Asona clan.He was elected from only the Asona Kusi Boadum Royal lineage.[18] However, a tradition was invented which made the occupation of the queen's stool a restricted privilege of the Asona Kusi Boadum dynasty. Queens who occupied the Kusi Boadum Stool remembered in the traditions were Poa Yiadom, Ninkyi Saaben and Akosua Serwaa. Kings that the Asona Kusi Boadum Royal lineage produced were:Yaw Antori,Baayim, Kwabena Dwoben,Gyima Ankoana, Ketekyew, Baabu Achemfour, and Adu Kwame. The latest litigated with the people of Kona about the land they occupied. When Adu Kwame emerged victorious in the land suit, he distributed the land among the Asona, Ekona, Aduana, Bretuo, Agona and Oyoko clans that constituted the Tano-Dumase state.[19]

Kings produced by the Asona Amoadampan Royal lineage remembered in the traditions were: Owusu Ansah, Appia, Kwadwo Fodjour and Ketekyew II.The Asona Afomaso Royal Lineage also produced Kofi Darkwa and Appia. Traditions mentioned Afia Nikra and Yaa Akyiaa as members of the Asona Afomaso Royal who occupied the female stool in contravention of the people's constitutional custom. Nana Kofi Oduro relates that royals of Kusi Boadum's lineage were by tradition eligible to occupy the Ejisu stool. He contended that when Nana Gyikopim of Ejisu died, Nana Gyima from Tano-Dumase became the regent till Aboagye Agyei was enstooled as the permanent king.[20] Kwabena Antwi Boasiako also affirmed the dynastic relationship between Tano-Dumase people and Ejisu people.[21].

V. BOUNDARY NEIGHBOURS

At the peak of its dexterity and political prowess, the Tano-Dumase traditional state shared boundaries with Kona to the South at the Adoosu River; to the north with Agona at the Kumkum River area; to the east with Boforoyeduru at Adoosuagya area and to the west with Abrakaso on the Offin River.[22]

Later, several Akan groups flowed into Tano-Dumase. These groups were not only assimilated and integrated into the autochthonous population but also were given a material stake in the government. The Asene occupied the Gyaase division, the Aduana took the Kyidom; the Asona occupied the Nifa division; the Ekona clan also occupied the Akwamu division while the Bretuo took the Akyeamehene. Other Akan clans migrated into the Tano-Dumase traditional state either to escape wars or find opportunities there.

[18] Information obtained from Opanin Kwabena Poku at Tano-Dumase on the 30th of June ,2024.
[19] Information obtained from Opanin Kwabena Poku,at Tano-Dumase on 30th day of June,2024.
[20] Information obtained from Nana Kofi Duro on the 30th of June ,2024.
[21] Information obtained from Kwabena Antwi Boasiako on the 30th of June 2024.
[22] Ibid

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VI. THE ASENE MIGRATION

A section of the Asene clan of Agona and Afomaso led by Ampontua migrated and settled at Tano-Dumase. What occasioned the migration? Tomfour relates that his ancestors who once lived in Agona had a conflict with the Agona chief; consequently, they escaped to Afomaso. One group left Afomaso and headed towards Tano-Dumase.The Asene were integrated into the political organization. Nana Baabu,the King of Tano-Domase created the Gyaase stool for the Asene clan with Ampontua Panyin as the first occupant.Other occupants were:Yaw Mensa, Yaw Afrifa, Kwasi Boateng and Ampontua Kumah.The lattest died on the stool but his stool was not blackened to legitimize his office. Among the Akan, the Gyaase segment of the ruling class were according to the constitutional custom regarded as ''wives'' of the king because they engaged in such domestic services as cooking for the king. On account of their domestic engagement, they were given the title of ohene yere, the wife of the king.[23]

In the Gyaase division of the government, it was the Ampontua family line that had legitimacy of ascension to the Gyaase stool. Gyaase tradition relates that some members of the Asene of Tano-Dumase were related to Okomfo Anokye, the fetish priest who lived at Agona.[24] Available evidence relates that Ampontua Panin, who once became the Gyasehene of Tano-Boase was Okomfo Anokye's nephew. Others relatives of Anokye remembered in the tradition were: Yaw Mensah, Yaw Nnipa Antwi, Agya Attah, Adwoa Pokuaa, Afia Adantamu, Omenaa and Abena Amponfi.

Another batch of the Asene migrated from Amakom and Agona to join their kinsmen at Tano-Dumase. But according to their traditional constitution and custom, occupation of the Gyaase stool was an exclusive right and privilege of Ampontua's family line. One group of the Asene clan under the leadership of Yaw Afrifa and Kwasi Boateng journeyed to the Wenchi country in the present Bono East region of Ghana.

VII. THE ADUANA AND BRETUO MIGRATION

The Aduana and Bretuo versions of the local traditions assert that a section of the Aduana clan migrated from Ofinso and settled in the Tano-Dumase country. Like the Asene, the Aduana and the Bretuo clans were integrated into the Tano-Dumase traditional state and occupied established offices in the government.

VIII. THE OYOKO AND EKONA MIGRATION

Sections of the Oyoko and Ekona clans also trooped into the Tano-Domase country. All of these groups were attracted to the place as a result of the spiritual activities of the Tano deity.

[23] This title affirmed their domestic credentials because in traditional Akan society, domestic chores were done mainly by women.

[24] Information obtained from Nana Kwasi Boaten,an Asene royal at Tano-Dumase on 30th June,2024.

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IX. RELIGION AND TABOOS

The people of the Tano-Dumase traditional state were very religious. Gyekye contends that in all undertakings of the Africans, religion plays an important role. Being it cultivation, sowing harvesting eating, travelling, marriage, outdooring, funeral etc. religion is seen at work. But each African community had its own system of religious beliefs and practices.[25]

In puberty rights, religion is not down-played.[26] Adjaye claims that ritual practices are compatible with the African's way of life.[27] Odotei contends that in such social institutions as festivals, religious practices are inevitable and the deities and the ancestors are at the center of such religious practices.[28] Religion played a dominant role in the foundation of the Tano-Dumase traditional state. The Tano cult of Tano-Dumase was associated with the Tano River The location of the town followed the dictates of the Tano cult. It was for this reason why the name Tano that referred to the cult prefixed Odumase. In the traditional Tano-Dumase society, the Tano deity was venerated as a state god. It was consulted by the rulers whenever they wanted to embark on wars of expansion or migration and resettlement elsewhere. It was believed that the deity protected their lives and so failure to observe its rituals and taboos could inflict calamity on the people. Although the rivers Kobire, and Kumkum were all deified, and worshipped, the Tano River was considered the most powerful of all the deities. People travelled afar even to this day to consult it. Another river-God worthy to mention here was the Anyinasu deity. Rearing of goats at Tano-Dumase was tabooed because it was believed that the Tano deity disliked goats. Certain days were also tabooed because it was believed that on those days the deities became active in people lives. Days tabooed and set apart for the veneration of the deities were: Akwasidae, Sunday; Wukudae, Wednesday; and Fofie Friday

X. CONCLUSION

In this work, I have chronicled a history of origin and the foundation the Tano-Dumase traditional state and the creation of the Kusi Boadum royal dynasty. The work has revealed that the people of the Tano-Domase traditional state migrated from Saaman-Tamfoe in the Akyem area of the present-day Eastern region of Ghana. The Asona group settled in some places until they came to their final destination probably in the seventeenth century. Other such Akan clans as the Asene, Bretuo Oyoko and Aduana probably wanting to escape war or find opportunities elsewhere migrated into the Tano-Dumase country. The Asona migrants established a government of an Akan model with Kusi Boadum as the first King. To consolidate the state, King Kusi Boadum assimilated members of the other clans into the state's political structure to play roles specifically

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[26] Peter Sarpong, *Girls Nubility Rites in Ashanti* (Tema Ghana Publish 1977),pp.ix
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ascribed to them. Religiosity of the people couldn't be overemphasized. The Tano cult was the most senior deity of the state. The people's belief in deities was rooted in their world view; consequently, such taboos as not rearing picks was outlawed by the rulers of the state. The research has revealed the origin of the Mmoaninko festival of the Offinso traditional state. Besides, the reason for which Bonwire,Abrakaso.Anyinasu.Beposo and Tano-Dumase lost their sovereignty to Ejuso.

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[3] Madam Augustina Kusi, a retired Nurse, 65 years. She was interviewed at Kobedi-Chriaa near Sunyani

Nana Abena Amfiri,90 years old,HNo. AB 196, KEVEL RD, AZ-0332-6801 She was interviewed on the 28th of June 2024.

[4] Opanin Kwabena Opoku, HNo. NB 12, Linguist of the Asona Royal family, Tano-Dumase, 65 years old. He was interviewed on the 21st June 2024.

[5] Nana Yaa Owusuaa Ampem, Tanosohemaa, Abotia-Kronom Kumasi, 67 years was interviewed at her house on 20th June 2024.

[6] Opanin Kwabena Opoku, H/No. NB.12 Tano -Dumase, Linguist of the Asona Royal Family, Tano Odumase 65 years the 21st June 2024.

[7] Nana Kofi Aduro, HNo. AB 253, KEVEL RD AZ-0403-8768, a 70-year-old Royal of Asona Kusi Boadum Family and Adontenhene of Tano-Dumase was interviewed on 20th June 2024.

[8] Lawrence Kwabena Twumfour,HNo.NB 2, Nyamebekyere,Tano-Dumase,a Farmer and Former Assembly member, Ahenboboano, Electoral Area, 70 years old, Asene Family Head.

[9] Nana Kwasi Boaten, a member of the Asene Royal Clan. He is a linguist. Residence HNo. AB 173, KEVEL RD, AZ-0332-2410.

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Attitude of Dalit Parents towards Girls Education with respect to their Socio-economic Status in Muzaffarpur Division

Cyma Anjum
Assistant. Professor of Education, LNMCBM (Edu.Prog.) BRA Bihar University, Muzaffarpur.

***Abstract*—The advancement and betterment of society are significantly influenced by female education. The most effective weapon for transformation is education, which can lead to females' economic and social empowerment. An individual's propensity, manner, mood, and position to react favourably or unfavourably to an item, behaviour, person, institution, event, or any other obvious aspect of their reality are referred to as their attitude. It involves the intricate organisation of evaluative attitudes, feelings, and propensities for particular actions.**

The usefulness of attitude was emphasised as well by Krech and Crutchfield (1948) they described the attitude as the long-term organisation of cognitive, perceptual, affective, and motivational processes concerning specific elements of the individual's reality. Some authors make a distinction between an attitude that is expressed verbally and one that is expressed behaviourally; the latter must be inferred from overt behaviour, both verbal and nonverbal. Swami Vivekananda said there is no change in the welfare of the world unless the condition of women is improved. It is not possible for a bird to fly on one wing. Any national strategy to eradicate gender disparity in education and attain universal education must start with making education free and required. More female instructors who, can act as role models for girls and who might put parents of young girls at ease should be hired. Giving girls access to sports can also help achieve gender equity in the classroom.

***Index Terms*—Girl education, social empowerment, gender disparity, gender equity, female education.**

I. INTRODUCTION

Education is one of the major instruments of social change and it is the force, which brings changes in the traditional outlook of the people, and it develops insight for judging things in their context. It is assumed that more the percentage of educated people more will be the rate of development. The Latin word "Educare," which is the root of the English word “education,"

implies to nourish or cause to thrive (Patel, 1991). Education is essential for everybody in the society. Good (1959) defined attitude as the readiness to respond to or against a situation, person, or object in a particular way, such as with love or hate. According to Allport (1935), attitude is a mental and neurological state of readiness that is organised through experience and affects a person's response to all objects with which it is associated directly or dynamically. For Parents to send their daughters to school without hesitation, the schools need to be safeguarded (UNICEF, 2009). Due to the lack of separate restrooms, many girls quit school when their period starts. A lot of girls are kept at home to assist with chores. Early marriage customs, together with social conventions and values, lessen the value of educating girls. While educating a male is just like educating an individual, educating a girl is like educating a family. Compared to rural residents, urban residents are more concerned about their daughter's education (Rafique, et al., 2002). There is ample evidence that children from better educated parents more often go to school and tend to drop out less (UNESCO, 2010). Parents who have reached a certain educational level might want their children to achieve at least that level (Breen & Goldthorpe, 1997). For educational enrolment of girls, education of the mother might be especially important (Emerson & Portela Souza, 2007; Shu, 2004; Kambhampati & Pal, 2001; Fuller, Singer and Keiley, 1995). Mothers who have succeeded in completing a certain leve of education have experienced its value and know that it is within the reach of girls to complete that level.

In October 2005 the general conference of UNESCO approved the establishment of the International Centre of Women ‘s and Girl ‘s Education in Africa, under the auspices of UNESCO, with the goal of promoting the genuine participation of women in decision-making at the community, national, regional and international levels‖. Gender discrepancy has remained a vague issue from decades. This disparity exists in the educational contents also. If it is discussed in terms of higher education, the disparity and discrimination is much higher than other levels of education likewise primary and secondary education. In this regard Parents' attitude captures a very critical place in the educational matters of girls.

Education is the basic human right of every individual irrespective of sex, race or region. Investment in human capital development while ignoring the women, half of world's population, is not a feasible approach. Education is one of the most important fields where women have been deprived traditionally (Hashmi, Zafar, and Ali, 2010).

Education is considered as a significant instrument of change having strong correlation with the overall economic and social advancement of the country (Siddiqui, 2007). Higher level of women education usually leads to higher level of income source for women (Stromquist, 2001). In this way if every woman is educated, she will encounter to employment field and her many problems could be solved (Sharma, 2005).

II. SOCIO-ECONOMIC STATUS AND EDUCATION

The education of children is influenced by interplay of a range of factors at school, society and family, especially for the tribal children. For school participation, it is important that all the three

factors should be positive or at least one or two factors should be strongly favourable. Both in developed and developing countries, children from families with more socio-economic resources are more often enrolled in school. For wealthier families, the direct costs associated with education, such as fees, books and uniforms are less likely to be an obstacle. Opportunity costs of children not being able to help at home, at the family farm or by earning additional income through child labour, are also less important to them (Evangelista de Carvalho Filho, 2008; Basu, 1999).

Besides household wealth, the educational level and labour market position of the parents is expected to play a role. There is ample evidence that children from better educated parents more often go to school and tend to drop out less (UNESCO, 2010). Parents who have reached a certain educational level might want their children to achieve at least that level (Breen & Goldthorpe, 1997). For educational enrolment of girls, education of the mother might be especially important (Emerson & Portela Souza, 2007; Shu, 2004; Kambhampati & Pal, 2001; Fuller, Singer and Keiley, 1995). Mothers who have succeeded in completing a certain level of education have experienced its value and know that it is within the reach of girls to complete that level. Therefore, we expect them to use the power and insights derived from their higher education to make sure that their daughters are educated too (Smits & Gündüz-Hogör, 2006).

The income of the parents plays a strong determinant of children education. Regarding father‘s labour market position, we expect fathers who are in salaried employment to be more aware of the importance of education and hence to invest more in their children‘s education (Breen & Goldthorpe, 1997). The children themselves may also be more aware of the benefits of education. On the other hand, parents are less likely to invest in their children‘s education when direct occupational transmission or transference of capital is a viable option to obtain a good position in society for their children (Treiman & Ganzeboom, 1990; Blau & Duncan, 1967).

III. IMPORTANCE OF GIRL CHILD EDUCATION

The importance of education to human beings cannot be overemphasized. Education is a human right that should be accorded to all human beings solely by reason of being human. The relationship between education and development is well established such that education is a key index of development. The girl-child is a biological female offspring from birth to eighteen (18) years of age. This is the age before one becomes young adult. This period covers the crèche, nursery or early childhood (0 – 5 years), primary (6 – 12 years) and secondary school (12 – 18 years). During this period, the young child is totally under the care of the adult who may be her parents or guardians and older siblings. It is made up of infancy, childhood, early and late adolescence stages of development. During this period, the girl-child is malleable, builds and develops her personality and character. She is very dependent on the significant others, those on whom she models her behaviour, through observation, repetition and imitation. Her physical, mental, social, spiritual and emotional developments start and progress to get to the peak at the young adult stage. Education is the process of providing information to an inexperienced person

to help him/her develop physically, mentally, socially, emotionally, spiritually, politically and economically.

IV. OBJECTIVES OF THE STUDY

- To examine the attitudes of Dalit parents towards education of their girl child.
- To examine the attitudes of Dalit parents towards education of their girl child in relation to locale (rural & urban) variation.
- To examine the difference between the attitudes of Dalit parents having high socio-economic status and having low socio-economic status towards girls' education.
- To examine the difference between attitudes of above graduate Dalit parents and attitude of below graduate Dalit parents towards their girl child education.
- To examine the difference between the attitudes of Dalit parents having high socio-economic status and having low socio-economic status towards girls 'education in rural areas.
- To examine the difference between the attitudes of Dalit parents having high socio-economic status and having low socio-economic status towards girls' education in urban areas.

V. HYPOTHESIS OF THE STUDY

On the basis of the above objectives, the following hypotheses have been formulated:

- There would be no significant difference of Dalit Parents 'attitude towards girls' education.
- There would be no significant difference of Dalit Parents 'attitude towards girls 'education in relation to locale (rural & urban) variation.
- There would be no significant difference of Dalit Parents 'attitude towards girls' education in relation to type of family (Joint & Nuclear) variation.
- There would be no significant difference of Dalit Parents 'attitude towards girls 'education in relation to Socio-Economic Status variation.
- There would be no significant difference of Dalit Parents 'attitude towards girls' education in relation to education variation.
- There would be no significant difference between the attitudes of Dalit parents having high socio-economic status and having low socio-economic status towards girl's education in rural areas.

There would be no significant difference between the attitudes of Dalit parents having high socio-economic status and having low socio-economic status towards girls' education in urban areas.

VI. METHOD OF THE STUDY

For the present study, the descriptive method of research has been used. Descriptive research may be characterized as simply the attempt to determine, describe or identify, what is

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Descriptive research aims at casting light on current issues or problem through a process of data collection that enables them to describe the situation more completely than was possible without employing this method.

VII. RESEARCH DESIGN

It is a descriptive study which investigates the attitude of Dalit parents towards their girl child education. A.06 Block consists of 100 samples and B. 06 Block consists of 100 samples.

Sample

Samples were taken from A.06 Blocks of Muzaffarpur Division. A sample of 200 house hold (Parents) were selected by purposive Sampling Technique. The variables of the study are locale (Rural & Urban), Socio-Economic Status (High SES & Low SES), Education (Above graduate and below graduate).

Scale for measuring parents‟ attitude towards girls‟ education (2017) by Kalam, Uzma and Lal, Banwari was used for data collection.

Socio-Economic Status scale of Mishra (2014) had been used to determine the socio-economic background of parents of the girls children.

The test of significance of difference (‗t‘) between the means of two contrasting sub-samples was calculated to find out significant difference in two sub samples in relation to locale, socio-economic status, education and type of family.

Results:

One of the objectives of the study was to be found out if there exist any locale variation differences on Dalit Parents' attitude towards girls 'Education, therefore the null hypothesis was stated as there is no significant difference in Dalit Parents 'attitude towards girls 'Education in relation to locale variation‖.

It was found that there exists no significant difference between rural and urban Dalit Parents' attitude towards girls 'Education in relation to locale variation will be rejected. This finding was in conformity with the findings of Mingat, 2007; Shavit and Blossfeld, 1993; Jencks, 1972; Coleman et al., 1966, Sen, 1992, Caldwell, 1982 and Bauch 1991.

One of the objectives of the study was to be found out if there exist any type of family variation differences on Dalit Parents 'attitude towards girls' Education, therefore the null hypothesis was stated as there is no significant difference in Dalit Parents' attitude towards girls 'Education in relation to type of family variation.

In order to find out differences if any of the scores on Dalit Parents 'attitude towards girls'Education of joint and nuclear family, the test of significance of difference between the means of two sub samples were calculated and tested for significance.

The obtained value 3.07 is greater than the tabular value at 0.05 levels 1.98 and at 0.01 level 2.63 so it is significant and the null hypothesis that states there exist no significant difference between

Dalit Parents' attitude towards girls 'Education in relation to type of family variation will be rejected. This finding was in conformity with the findings of Dornbusch and Ritter (1988), Bogunović Blanka and Polovina Nada (2007) and Useem (1992).

The objectives of the present study was to find out if there exist any Socio-Economic Status variation differences on Dalit Parents' attitude towards girls 'Education, therefore the null hypothesis was stated as there is no significant difference in Dalit Parents 'attitude towards girls

VIII. EDUCATION IN RELATION TO SOCIO-ECONOMIC STATUS VARIATION.

In order to find out differences if any of the scores on Dalit Parents' attitude towards girls' Education of High Socio-Economic Status and Low Socio-Economic Status, the test of significance of difference between the means of two sub samples was calculated and tested for significance. The obtained value 3.83 is greater than the tabular value at 0.05 levels 1.98 and at 0.01 level 2.63 so it is significant and the null hypothesis that states there exist no significant difference between the Socio-Economic Status variation of Dalit Parents 'attitude towards girls 'Education will be rejected. This finding was in conformity with the findings of Breen & Goldthorpe,1997, Huisman, Rani, and Smits, 2010, Bhalotra & Heady, 2003; Basu, Das and Dutta, 2003, Evangelista de Carvalho Filho, 2008; Mingat, 2007; Shavit and Blossfeld, 1993; Jencks, 1972; Coleman et al., 1966 and Bauch 1991.

Another objective of the study was to find out if there exist any education variation differences on Dalit Parents 'attitude towards girls 'Education, therefore the null hypothesis was stated as there is no significant difference in Dalit Parents 'attitude towards girls 'Education in relation to education variation.

In order to find out differences if any of the scores on Dalit Parents' attitude towards girls' Education of above graduate and below graduate parents, the test of significance of difference between the means of two sub samples was calculated and tested for significance. The obtained value 2.92 is greater than the tabular value at 0.05 levels 1.98 and at 0.01 level 2.63 so it is significant and the null hypothesis that states there exist no significant difference between the education variation of Dalit Parents' attitude towards girls 'Education will be rejected. This finding was in conformity with the findings of Dornbusch and Ritter (1988), Emerson & Portela Souza, 2007, Breen and Goldthorpe, (1997).

Socio-Economic Status variation differences on Rural Dalit Parents‟ attitude towards girls‟ Education

An important objective of the study was to b find out if there exist any Socio-Economic Status variation differences on rural Dalit parents' attitude towards girls 'Education, therefore the null hypothesis was stated as there is no significant difference in rural Dalit parents' attitude towards girls 'Education in relation to Socio-Economic Status variation‖.

In order to find out differences if any of the scores on rural Dalit Parents' attitude towards girls' Education of High Socio-Economic Status and Low Socio-Economic Status, the test of

significance of difference between the means of two sub samples was calculated and tested for significance. The result has been presented in the following table:

The obtained value 3.81 is greater than the tabular value at 0.05 levels 1.98 and at 0.01 level 2.63 so it is significant and the null hypothesis that states there exist no significant difference between the Socio-Economic Status variation of rural Dalit parents' attitude towards girls 'Education will be rejected. This finding was in conformity with the findings of Breen & Goldthorpe,1997, Huisman, Rani, and Smits, 2010, Bhalotra & Heady, 2003; Basu, Das and Dutta, 2003, Evangelista de Carvalho Filho, 2008; Mingat, 2007; Shavit and Blossfeld, 1993; Jencks, 1972; Coleman et al., 1966 and Bauch 1991.

Socio-Economic Status variation differences on Urban Dalit Parents‟ attitude towards girls‟ Education

The main objectives of the study was to be found out if there exist any Socio-Economic Status variation differences on urban Dalit parents' attitude towards girls 'Education, therefore the null hypothesis was stated as there is no significant difference in urban Dalit parents' attitude towards girls 'Education in relation to Socio-Economic Status variation‖.

In order to find out differences if any of the scores on urban Dalit Parents 'attitude towards girls' Education of High Socio-Economic Status and Low Socio-Economic Status, the test of significance of difference between the means of two sub samples was calculated and tested for significance.

The obtained value 3.65 is greater than the tabular value at 0.05 levels 1.98 and at 0.01 level 2.63 so it is significant and the null hypothesis that states there exist no significant difference between the Socio-Economic Status variation of urban Dalit Parents 'attitude towards girls 'Education will be rejected. This finding was in conformity with the findings of Breen & Goldthorpe,1997, Huisman, Rani, and Smits, 2010, Bhalotra & Heady, 2003; Basu, Das and Dutta, 2003, Evangelista de Carvalho Filho, 2008; Mingat, 2007; Shavit and Blossfeld, 1993; Jencks, 1972; Coleman et al., 1966, Sen, 1992, Caldwell, 1982 and Bauch 1991.

IX. CONCLUSION

Discrimination is an age-old concept which can hardly be eradicated in the same pace of time itself, it is a natural phenomenon so it is difficulty and sometimes improper to totally eradicate it in society. But effects should be geared to minimize and abridge it adverse effect in society in order to achieve harmonious co-existence. Every society on the earth imbibes this conception whatever it does either in the family cycle, the village cycle of the state cycle. It also gives a challenge to those discriminated against. There are five factors militating against the female children compulsory education. Though, the fourth factor is particularly partly attributed to both the parents and the daughters themselves. The traditional cum- cultural factor maintains the parents prerogative is divine, no culture or tradition can survive if it is automatically affected by social exchange. The parents are likely to send their daughters to schools. It such ideas did not

infringe the laid down traditions and custom of the society. The society will not tolerate the violation of its established beliefs and the word of God as prophesized by the Holy prophet and elders by sending the female children of the believers to schools. It is religious that caters for the children are moral and spiritual uplifted. The socio-economic factors concern the social and the economic steward of the people. The social economic factor is variable. It is subject to change depending on the moment of the society (either positive or negative) whether the people of West Bengal will have low or high socio-economic depends solely on the present administration. The prevailing economic sector or situation will determine whether the parents could afford to send their daughter to school or not. The prestigious factors are ascribable to the whim and caprices of the parents and the daughters alike. Both of them have lukewarm attitude for the acquisition of formal education. Some of the parents prefer their daughter becoming mother that to pursue education through few of them would want their daughter to achieve both motherhood and attainment of academic goals simultaneously. The daughters derive joy to have changed their status in life from sprinter hood to motherhood than to relatively postpone that unique status to pursue academy. They are complacent because they are fulfilled the natural assignment. The discriminatory perspective based on sex indicates the society is selective in employing labour into the workforce. Male are more regarded than female. Women employment is taken by some employees as supplementary to their marital and household management it is cultural factor maintains the parents prerogative is divine, no culture or tradition can survive if it is automatically affected by social exchange. The parents are likely to send their daughters to schools. It such ideas did not infringe the laid down traditions and custom of the society. The society will not tolerate the violation of its established beliefs and the word of God as prophesized by the Holy prophet and elders by sending the female children of the believers to schools. It is religious that caters for the children are moral and spiritual uplifted. The socio-economic factors concern the social and the economic steward of the people. The social economic factor is variable. It is subject to change depending on the moment of the society (either positive or negative) whether the people of Muzaffarpur division will have low or high socio-economic depends solely on the present administration. The prevailing economic sector or situation will determine whether the parents could afford to send their daughter to school or not. The prestigious factors are ascribable to the whim and caprices of the parents and the daughters alike. Both of them have lukewarm attitude for the acquisition of formal education. Some of the parents prefer their daughter becoming mother that to pursue education through few of them would want their daughter to achieve both motherhood and attainment of academic goals simultaneously. The daughters derive joy to have changed their status in life from sprinter hood to motherhood than to relatively postpone that unique status to pursue academy. They are complacent because they are fulfilled the natural assignment. The discriminatory perspective based on sex indicates the society is selective in employing labour into the workforce. Male are more regarded than female. Women employment is taken by some employees as supplementary to their marital and household management.

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FinTech and Digital Payments: Impact on Financial Inclusion and the Growth of Modern Commerce

Dr. Saddam Hussain
PHD, MBA, LLM, M.COM, LLB, B.COM MINDS NXT TECHNO VISION PVT LTD

***Abstract*—Financial Technology (FinTech) and digital payments have emerged as major forces transforming the global financial and commercial landscape. The rapid development of smartphones, internet connectivity, digital banking, mobile applications, digital wallets, real-time payment systems, artificial intelligence, blockchain, cloud computing, and application programming interfaces has changed the manner in which individuals and businesses access financial services and conduct commercial transactions. Digital payments have reduced dependence on physical cash, increased transaction speed, enabled remote commerce, and created new opportunities for individuals and enterprises that have historically faced barriers to formal financial services.**

This article examines the role of FinTech and digital payments in promoting financial inclusion and supporting the growth of modern commerce. The study adopts a conceptual and descriptive research methodology based on secondary sources, including academic literature, institutional publications, industry reports, books, and international development research. The article examines the relationship between FinTech innovation, digital payment adoption, access to financial services, small-business development, consumer behaviour, and commercial growth. It also discusses the contribution of digital financial services to banking access, savings, credit, insurance, remittances, entrepreneurship, and electronic commerce. The study identifies important challenges, including cybersecurity, fraud, data privacy, digital exclusion, financial illiteracy, technological dependence, regulatory uncertainty, and unequal access to digital infrastructure. The article argues that FinTech can contribute significantly to inclusive economic development when digital financial services are affordable, accessible, secure, transparent, and supported by appropriate regulation. The study concludes that FinTech and digital payments are not merely technological innovations but important components of modern commercial infrastructure, capable of strengthening financial inclusion, reducing transaction costs, expanding market participation, and supporting the growth of digital commerce.

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***Index Terms*—FinTech, Digital Payments, Financial Inclusion, Digital Banking, Financial Technology, Modern Commerce, Mobile Payments, Digital Finance, E-Commerce, Financial Services**

I. INTRODUCTION

The financial sector has experienced substantial technological transformation during the last two decades. Traditional banking and payment systems that relied heavily on physical branches, cash transactions, paper documentation, and face-to-face interaction are increasingly being supplemented by digital financial services.

Financial Technology, commonly referred to as FinTech, represents the application of technology to financial services. FinTech includes a broad range of activities such as digital payments, mobile banking, digital lending, online investment platforms, insurance technology, blockchain applications, automated financial advice, and financial data analytics.

Among these developments, digital payments have become particularly important to modern commerce. Consumers and businesses can increasingly transfer money, pay for goods and services, receive salaries, settle invoices, and conduct cross-border transactions electronically.

Digital payments also have important implications for financial inclusion. Individuals without convenient access to traditional banking infrastructure may gain access to formal financial services through mobile phones and digital platforms.

Financial inclusion refers broadly to the availability and effective use of affordable, appropriate, and responsible financial services by individuals and businesses. Access to accounts, payments, savings, credit, insurance, and other financial services can support economic participation and household and business resilience.

The relationship between FinTech, financial inclusion, and commerce is therefore multidimensional. Digital financial services can reduce transaction costs, expand market access, improve payment efficiency, and enable small businesses to participate in digital markets.

However, digital finance also creates risks. Cybersecurity threats, fraud, data misuse, inadequate consumer protection, lack of digital literacy, and exclusion of individuals without appropriate technology can limit the benefits of FinTech.

This article examines how FinTech and digital payments are influencing financial inclusion and contributing to the growth of modern commerce.

II. CONCEPT OF FINTECH

FinTech can be defined as the application of technological innovation to the provision, delivery, management, and consumption of financial services.

Major FinTech segments include:

1. Digital payments.
2. Mobile banking.

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3. Digital lending.
4. Online investment services.
5. InsurTech.
6. RegTech.
7. Wealth technology.
8. Blockchain and distributed ledger applications.
9. Digital remittances.
10. Financial data analytics.
11. Embedded finance.
12. Artificial Intelligence-based financial services.

FinTech firms increasingly operate alongside traditional banks, payment institutions, technology companies, marketplaces, and other financial-service providers.
The result is an increasingly interconnected financial ecosystem.

III. CONCEPT OF DIGITAL PAYMENTS

Digital payments involve the electronic transfer of funds between individuals, businesses, institutions, or financial accounts.
Examples include:

- Bank transfers.
- Mobile payments.
- Digital wallets.
- QR-code payments.
- Card payments.
- Internet banking.
- Real-time payment systems.
- Electronic fund transfers.
- Contactless payments.

Digital payments have become a fundamental component of e-commerce because online transactions generally require electronic settlement mechanisms.

IV. FINANCIAL INCLUSION: CONCEPT AND IMPORTANCE

Financial inclusion involves ensuring that individuals and businesses can access and effectively use appropriate financial services at reasonable cost.
Important dimensions of financial inclusion include:

- Access to transaction accounts.
- Affordable payment services.
- Savings facilities.
- Credit.
- Insurance.

- Remittance services.
- Financial information.
- Consumer protection.

Financial inclusion is important because access to financial services can support:

- Household financial management.
- Entrepreneurship.
- Business investment.
- Savings.
- Risk management.
- Economic participation.

For businesses, particularly small and micro enterprises, access to digital financial services can facilitate payments, record keeping, financing, and participation in formal markets.

V. OBJECTIVES OF THE STUDY

The major objectives of this article are:

1. To examine the concept and development of FinTech.
2. To analyse the role of digital payments in modern commerce.
3. To examine the relationship between FinTech and financial inclusion.
4. To assess the contribution of digital payments to economic and commercial activity.
5. To examine the impact of FinTech on small businesses and entrepreneurs.
6. To identify major challenges associated with digital financial services.
7. To examine the role of digital payments in e-commerce.
8. To propose strategies for promoting responsible and inclusive FinTech development.
9. To examine the future prospects of FinTech and digital payments.

VI. RESEARCH METHODOLOGY

This article adopts a conceptual and descriptive research methodology based on secondary data and published literature.

The study draws information from:

- Academic journals.
- Books.
- Government publications.
- Central-bank publications.
- International organizations.
- Financial-sector reports.
- Industry research.
- Existing studies on FinTech and financial inclusion.

The literature is analysed thematically to understand how technological innovation in finance affects financial access and commercial development.

The study does not employ primary survey data. Therefore, its conclusions are conceptual rather than statistically generalizable.

VII. LITERATURE REVIEW

Research on financial inclusion has established that access to appropriate financial services can contribute to economic participation and development.

Beck, Demirgüç-Kunt, and Levine examined the relationship between financial development and economic activity and highlighted the importance of access to financial services.

Demirgüç-Kunt and colleagues have emphasized the importance of account ownership and digital financial services in expanding financial inclusion.

Arner, Barberis, and Buckley examined the development of FinTech and its implications for financial services, identifying technology as an important force reshaping financial-sector structures.

Philippon examined the economics of FinTech and discussed its potential to reduce costs and improve competition in financial services.

Gomber, Koch, and Siering identified FinTech as a broad transformation of financial services involving digital technologies, new business models, and changing relationships among financial institutions and consumers.

The literature broadly indicates that FinTech can increase accessibility and efficiency, although outcomes depend on infrastructure, regulation, digital literacy, consumer protection, and market conditions.

VIII. EVOLUTION OF DIGITAL PAYMENTS

The development of digital payments can be viewed in several stages.

Stage 1: Electronic Banking

Banks began offering electronic account-management and transfer services.

Stage 2: Card-Based Payments

Debit and credit cards expanded electronic payment acceptance.

Stage 3: Internet Banking

Consumers gained the ability to conduct financial transactions through online banking platforms.

Stage 4: Mobile Payments

Smartphones enabled consumers to initiate transactions through mobile applications.

Stage 5: Real-Time Digital Payments

Real-time payment infrastructure enabled rapid transfers between accounts.

Stage 6: Embedded and Intelligent Payments

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Financial services increasingly became integrated into e-commerce platforms, applications, and digital ecosystems.
This evolution has significantly reduced the physical barriers associated with financial transactions.

IX. FINTECH AND FINANCIAL INCLUSION

FinTech can promote financial inclusion through several mechanisms.

9.1 Increased Accessibility

Digital financial services can reach consumers beyond the geographical coverage of traditional branches.
Mobile technology can allow customers to access financial services remotely.

9.2 Lower Transaction Costs

Digital systems can reduce costs associated with physical branches, cash handling, paperwork, and certain types of financial intermediation.

9.3 Simplified Account Access

Digital onboarding and remote verification can make it easier for eligible customers to access formal financial services.

9.4 Digital Credit

FinTech platforms can use transaction and alternative data to support credit assessment, potentially expanding access to financing.

9.5 Digital Savings

Mobile and online platforms can make savings products more accessible.

9.6 Digital Insurance

Technology can simplify insurance distribution and claims processes.

9.7 Remittances

Digital platforms can make domestic and international transfers faster and more convenient.

X. DIGITAL PAYMENTS AND MODERN COMMERCE

Digital payments are essential infrastructure for modern commerce.
The relationship can be represented as:

Digital Payment Infrastructure

↓

Faster and More Convenient Transactions
↓
Higher Consumer and Business Participation
↓
Expansion of E-Commerce and Digital Markets
↓
Growth of Modern Commerce

Businesses can accept payments from customers without requiring physical cash.
Consumers can purchase products remotely.
Suppliers can receive electronic payments.
Employees can receive salaries digitally.
Governments and organizations can distribute funds electronically.
Thus, digital payments support multiple layers of the commercial ecosystem.

XI. FINTECH AND SMALL AND MEDIUM ENTERPRISES

Small and medium enterprises (SMEs) are important participants in modern commerce.
FinTech can support SMEs through:

- Digital payments.
- Digital bookkeeping.
- Online banking.
- Digital lending.
- Cash-flow management.
- Invoice financing.
- Financial analytics.
- Online marketplaces.

Digital payment records can also provide businesses with transaction histories that may support financial planning and, where appropriate, credit assessment.
However, SMEs may face challenges such as technology costs, cybersecurity risks, lack of digital skills, and dependence on third-party platforms.

XII. DIGITAL PAYMENTS AND E-COMMERCE

The growth of e-commerce depends significantly on reliable digital payment systems.
The typical online transaction can be represented as:

Product Search
↓
Product Selection
↓

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Digital Checkout
↓
Payment Authentication
↓
Electronic Payment
↓
Order Confirmation
↓
Delivery
↓
Post-Purchase Service

Digital payments reduce friction within this process.
Multiple payment options can also improve consumer convenience and reduce abandoned transactions.

XIII. DIGITAL PAYMENTS AND CONSUMER BEHAVIOUR

The availability of digital payment methods can influence consumer purchasing behaviour.
Digital payments provide:

- Convenience.
- Speed.
- Transaction records.
- Remote purchasing capability.
- Reduced dependence on cash.
- Integration with mobile applications.

However, easy payment mechanisms may also reduce the psychological barriers associated with spending. Businesses and regulators should therefore promote responsible consumer protection and transparent pricing.

XIV. FINTECH AND ENTREPRENEURSHIP

FinTech can reduce some barriers to entrepreneurship.
Entrepreneurs can use digital platforms to:

- Receive customer payments.
- Pay suppliers.
- Manage expenses.
- Access financial information.
- Apply for financing.
- Sell products online.

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- Reach customers beyond local markets.

Digital financial infrastructure can therefore support entrepreneurship and formalization.

XV. ROLE OF ARTIFICIAL INTELLIGENCE IN FINTECH

Artificial Intelligence has become an important component of modern financial technology.
Applications include:
Fraud Detection
AI can identify unusual transaction patterns.
Credit Assessment
Machine-learning models can analyze relevant data to support credit-risk assessment.
Customer Service
AI-powered assistants can answer routine customer questions.
Financial Forecasting
AI can support prediction of financial trends and cash-flow requirements.
Personalization
Financial platforms can recommend products or services based on customer needs and behaviour.
Compliance
AI can support transaction monitoring and other compliance processes.
However, AI-based financial services require careful governance because inaccurate or biased models can create significant consumer and financial risks.

XVI. BLOCKCHAIN AND DIGITAL FINANCE

Blockchain and distributed ledger technologies have attracted significant attention in financial services.
Potential applications include:

- Transaction recording.
- Digital identity.
- Asset tracking.
- Cross-border settlement.
- Smart contracts.
- Supply chain finance.

The commercial value of blockchain depends on the specific application, technical feasibility, regulatory requirements, and economic benefits.

Blockchain should therefore be evaluated as one possible technological infrastructure rather than as a universal solution.

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XVII. EMBEDDED FINANCE

Embedded finance involves integrating financial services directly into non-financial digital platforms.

Examples include:

- Payments within e-commerce platforms.
- Financing offered during online purchases.
- Insurance embedded into travel or product transactions.
- Digital financial services integrated into business applications.

Embedded finance can make financial services more convenient because users do not necessarily need to leave the platform they are using.

XVIII. CROSS-BORDER COMMERCE AND DIGITAL PAYMENTS

Digital payments can support international commerce by facilitating electronic settlement between buyers and sellers in different jurisdictions.

Potential benefits include:

- Faster transactions.
- Improved transparency.
- Reduced dependence on physical payment instruments.
- Easier participation in international e-commerce.

However, cross-border digital payments involve additional considerations such as:

- Foreign-exchange conversion.
- Regulatory compliance.
- Anti-money-laundering requirements.
- Data protection.
- Payment-system interoperability.
- Cross-border fraud.

XIX. DIGITAL PAYMENTS AND THE INFORMAL ECONOMY

Digital payments can contribute to the formalization of economic activity by creating electronic transaction records.

Potential benefits include:

- Better business records.
- Easier financial management.
- Greater visibility of cash flows.
- Potential access to formal financial services.
- Improved transaction transparency.

However, digitalization should not automatically be treated as a substitute for cash in every context. Individuals and businesses may face infrastructure, affordability, privacy, and digital-literacy constraints.

XX. CHALLENGES TO FINANCIAL INCLUSION THROUGH FINTECH

Although FinTech creates opportunities, several barriers remain.

20.1 Digital Divide

Individuals without smartphones, internet access, or reliable connectivity may remain excluded.

20.2 Financial Literacy

Consumers may not fully understand digital financial products.

20.3 Digital Literacy

Limited technological skills can reduce effective usage.

20.4 Cybersecurity

Digital financial systems are attractive targets for cybercriminals.

20.5 Fraud

Phishing, identity theft, social engineering, unauthorized transactions, and other forms of fraud can undermine trust.

20.6 Data Privacy

FinTech businesses often process substantial amounts of personal and financial information.

20.7 Regulatory Complexity

Rapid technological innovation can create challenges for regulators.

20.8 Algorithmic Bias

Automated financial decisions may produce unfair outcomes if models or data are biased.

20.9 Infrastructure Limitations

Poor connectivity and unreliable digital infrastructure can limit access.

XXI. CYBERSECURITY AND CONSUMER PROTECTION

Security is a fundamental requirement for digital finance.

FinTech organizations should implement:

1. Strong authentication.

2. Encryption.
3. Secure software development.
4. Transaction monitoring.
5. Fraud detection.
6. Customer alerts.
7. Incident-response mechanisms.
8. Employee cybersecurity training.
9. Data-access controls.
10. Regular security assessments.

Consumer protection should also include:

- Transparent fees.
- Clear terms and conditions.
- Effective complaint mechanisms.
- Fraud reporting procedures.
- Appropriate dispute resolution.

Trust is essential for the sustainable growth of digital finance.

XXII. REGULATORY ENVIRONMENT

The growth of FinTech requires an appropriate regulatory framework.
Regulators must balance:
Innovation ↔ Consumer Protection ↔ Financial Stability ↔ Competition
Regulation should encourage responsible innovation while protecting consumers and maintaining the integrity of financial systems.
Important regulatory areas include:

- Data protection.
- Payment security.
- Consumer protection.
- Digital identity.
- Cybersecurity.
- Anti-money laundering.
- Competition.
- Financial stability.

Regulatory frameworks also need to remain adaptable as technology develops.

XXIII. FINTECH AND GENDER AND SOCIAL INCLUSION

Digital financial services have the potential to increase access among groups that may face barriers to traditional financial services.

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Mobile and digital platforms can potentially improve access to:

- Payments.
- Savings.
- Credit.
- Insurance.
- Remittances.

However, technology does not automatically eliminate social and economic inequalities. Digital inclusion policies must address affordability, literacy, infrastructure, accessibility, and consumer protection.

XXIV. FINTECH AND SUSTAINABLE COMMERCE

Digital financial technologies can support more efficient commercial processes.
Potential contributions include:

- Reduced paper-based transactions.
- Digital documentation.
- Efficient payment processing.
- Improved financial monitoring.
- Better resource allocation.

Digital platforms may also facilitate access to financial products associated with sustainable activities.
Nevertheless, FinTech infrastructure itself consumes energy and physical resources, meaning that sustainability should be evaluated across the entire digital financial ecosystem.

XXV. CONCEPTUAL FRAMEWORK

The relationship between FinTech, financial inclusion, and modern commerce can be represented as follows:

Technological Innovation
↓
FinTech Services + Digital Payment Infrastructure
↓
Accessibility + Affordability + Convenience + Speed
↓
Financial Inclusion
↓
Greater Consumer and Business Participation
↓
E-Commerce + Entrepreneurship + Digital Markets
↓

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Growth of Modern Commerce
↓
Economic and Business Development

The framework suggests that technology contributes to commercial development partly by reducing barriers to financial participation.

XXVI. FINDINGS OF THE STUDY

The conceptual analysis identifies the following major findings:
Finding 1: FinTech can expand financial access
Digital financial services can reach consumers and businesses beyond traditional physical banking infrastructure.
Finding 2: Digital payments support modern commerce
Electronic payments enable remote transactions and facilitate e-commerce.
Finding 3: FinTech can reduce transaction costs
Digital processes can reduce certain administrative, payment, and transaction costs.
Finding 4: SMEs can benefit from digital finance
Digital payments, online banking, and FinTech financing can support small-business operations.
Finding 5: Digital finance can encourage entrepreneurship
Accessible payment and financial services can lower some barriers to starting and operating businesses.
Finding 6: Technology creates new risks
Cybersecurity, fraud, privacy, and digital exclusion remain significant challenges.
Finding 7: Trust is essential
Consumers and businesses are more likely to use digital financial services when they perceive them as secure, reliable, transparent, and fairly regulated.
Finding 8: Regulation is critical
Responsible FinTech development requires regulatory frameworks that balance innovation and protection.

XXVII. RECOMMENDATIONS

Based on the analysis, the following recommendations are proposed:

1. Governments and financial institutions should promote affordable digital financial infrastructure.
2. Digital financial services should be designed for accessibility and ease of use.
3. Financial and digital literacy programs should be strengthened.
4. Strong cybersecurity standards should be implemented across digital payment systems.
5. Consumers should receive clear information regarding fees, risks, and terms.

6. FinTech firms should adopt robust data-protection practices.
7. Regulators should encourage innovation while maintaining financial stability and consumer protection.
8. SMEs should be supported in adopting digital payment and financial-management technologies.
9. Interoperability among payment systems should be encouraged where appropriate.
10. Fraud detection and customer-protection mechanisms should be continuously improved.
11. AI-based financial decisions should be subject to appropriate monitoring and human oversight.
12. Digital inclusion programs should address barriers related to connectivity, affordability, disability, and digital literacy.
13. Financial institutions should collaborate with technology providers to improve secure digital services.
14. Consumers should be educated about cybersecurity, fraud prevention, and responsible digital finance.

XXVIII. FUTURE TRENDS IN FINTECH AND DIGITAL PAYMENTS

The future financial ecosystem is likely to be influenced by several developments.

28.1 Artificial Intelligence

AI will increasingly support fraud detection, customer service, financial analysis, and personalization.

28.2 Embedded Finance

Financial services will increasingly be integrated into non-financial digital platforms.

28.3 Real-Time Payments

Instant transaction systems are likely to become increasingly important for consumers and businesses.

28.4 Digital Identity

Secure digital identity systems may simplify access to financial services.

28.5 Open Banking and APIs

Greater integration between financial institutions and technology platforms may create new financial products and services, subject to applicable regulatory frameworks.

28.6 Digital Lending

Technology-enabled credit assessment may expand access to financing while increasing the need for responsible lending.

28.7 Cross-Border Digital Commerce

Improved digital payment infrastructure may facilitate international e-commerce and remittances.

XXIX. CONCLUSION

FinTech and digital payments have become important components of the modern commercial ecosystem. By enabling faster, more convenient, and increasingly accessible financial transactions, digital technologies can support financial inclusion and expand participation in commerce.

Digital payments are particularly important because they connect consumers, businesses, financial institutions, and digital marketplaces. They facilitate e-commerce, support small businesses, enable remote transactions, and create electronic records that can strengthen financial management.

FinTech also creates opportunities beyond payments. Digital lending, mobile banking, financial analytics, AI-enabled services, digital insurance, embedded finance, and other innovations are changing the structure of financial services.

However, technology alone cannot guarantee financial inclusion. Individuals may remain excluded because of inadequate connectivity, limited digital literacy, affordability constraints, lack of trust, or insufficient consumer protection. Similarly, cybersecurity threats, fraud, privacy risks, algorithmic bias, and regulatory uncertainty can undermine the benefits of digital finance.

The central conclusion of this article is that FinTech and digital payments can serve as important enablers of financial inclusion and modern commerce when technological innovation is combined with responsible regulation, strong cybersecurity, consumer protection, digital literacy, and inclusive infrastructure.

The future of commerce will increasingly depend on seamless integration between financial and digital technologies. Organizations that provide secure, accessible, transparent, and customer-oriented financial services will be better positioned to participate in the expanding digital economy. At the same time, policymakers and financial institutions must ensure that technological progress does not create new forms of exclusion.

FinTech should therefore be understood not merely as a technological development but as a structural transformation of financial and commercial systems. Its long-term contribution to economic development will depend on whether innovation can be translated into broader access, lower transaction costs, greater trust, responsible financial participation, and sustainable commercial growth.

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Artificial Intelligence Adoption in Recruitment and Quality of Hire in Startups the Mediating Role of Data-Driven Decision-Making

[1]D. S. Carmel Priyadarshini, [2]Dr. Tamil Selvi J
[1]Research Scholar, Annamalai University
[2]Associate Professor & Research Supervisor, Annamalai University

***Abstract*—Artificial Intelligence (AI) is revolutionizing the recruitment process, enabling organisations to automate their candidate assessment, gain insights from data, and make informed hiring decisions. In this conceptual paper, the authors explore how AI use in the recruitment process relates to startup organizations' quality of hire, suggesting a mediating role for data-driven decision-making. AI adoption is defined in terms of the use of AI for résumé screening, AI chatbots, predictive analytics, and recruitment automation. The paper builds on the current body of research on AI and HRM, and data-driven recruitment, and suggests that the use of AI will improve the quality of hire and data-driven decision making in HRM. It also believes that decision-making based on data enables the systematic and evidence-based evaluation of candidates, which leads to better hiring results from AI-generated data. The proposed framework deals with startups, which is a relatively under-researched context of an organization with critical talent demands, rapid growth, and limited resources. The paper provides a narrow focus for the future of empirical study on AI assisted recruitment.**

***Index Terms*—Artificial Intelligence; AI Adoption; Recruitment; Data-Driven Decision-Making; Quality of Hire; Startups; Talent Acquisition.**

I. INTRODUCTION

Artificial Intelligence (AI) is transforming Human Resource Management (HRM) and is altering the way organizations obtain, handle and utilize information about their workforce. In HRM, one of the most significant fields is recruitment, where there is a massive amount of data about candidates, and a variety of processes can be streamlined and accelerated through AI. AI can help in résumé screening, communication with applicants, applicant matching, predictive evaluation, and automation of the recruitment process. AI is therefore also seen by many as a means to help

organizations identify and select talent, rather than a technology that should simply be used in administration (Hmoud & Várallyai, 2021; Horodyski, 2023).

AI's role in recruitment is even more prominent in startups. Generally, start-ups function in a fluid market where resources are limited, roles change quickly, structures are small and it is important to hire good staff members fast for start-ups. In these circumstances, the selection of staff can have significant impact as it is possible for individual staff members to carry out more than one role and therefore to have a direct impact on the development of the organisation. The consequences of a bad hiring decision can be quite expensive, while hiring the right person for the right role and the right company can boost the startup's ability to expand. One way to tackle these challenges is by using AI-driven recruitment tools, which can help startups systematically extract data from candidates and inform better hiring decisions.

But, quick adoption of AI doesn't always translate to better hiring results. The usefulness of AI is partly dependent on how organizations use information created by the AI to make managerial decisions. This is a reminder of the need for data driven decision making, where recruitment decisions are made based on targeted data, analytic evidence and a structured approach, rather than largely on intuition and unstructured judgement. Data analytics research has shown that analysing workforce data can enhance evidence-based HR decision making by transforming workforce data into actionable insights (Shet et al., 2021). Specifically, studies on the use of AI in recruitment highlight the link between data quality, AI assisted automation and data informed hiring decisions (Purohit & Banerjee, 2025).

The process of decision making could ultimately affect quality of hire, defined as how well-chosen employees have the competencies, performance potential and job-related attributes that the organization needs. While AI can give insights to a candidate, it's only when they're interpreted correctly and integrated into the recruitment process that they add value to the organisation. In this way, data-driven decision making could be one of the key ways that AI helps to improve hiring outcomes.

Existing studies on AI in recruitment have focused on various aspects, such as technological adoption, recruiter attitudes, automation, fairness, and applicant responses, but have tended to analyse these topics individually. Not as much focus has been placed on the positive impact of AI use on the hiring process, especially in startups. To tackle this gap, the current conceptual study focuses on the link between AI use in recruitment and QOH and introduces data driven decision making as the mediator between the two. The study builds upon this trajectory and examines a parsimonious model that not only addresses the potential of AI to improve hiring but also suggests how that value can be achieved via evidence-based decisions in startups.

II. ARTIFICIAL INTELLIGENCE ADOPTION IN RECRUITMENT

Artificial Intelligence (AI) Adoption in Recruitment involves implementing and leveraging AI technologies within the organization to facilitate recruitment-related tasks such as attracting, screening, evaluating, communicating with, and selecting potential candidates. The digitization

of Human Resource Management (HRM) is changing the recruitment process from being mainly manual and intuitive to technology supported processes that can deal with huge amounts of candidate information. AI applications leverage technologies such as machine learning, natural language processing, algorithmic matching, predictive analytics, and generative AI to support recruitment efforts. Therefore, AI's use is not solely about simply buying AI recruitment software but also integrating intelligent technologies into the organizational recruitment processes and decisions (Pan et al., 2022).

There are multiple phases of the recruitment and selection process during which AI can be used. AI tools can be used to sift through resumes, compare candidate profiles to job requirements, communicate with candidates on the initial call, help with evaluations, and organize candidate details for the recruiters to assess. This type of application allows businesses to process the information of applicants at a rate and scale that may be hard to reach in using traditional, manual recruitment processes (Albert, 2021). Therefore, the recruitment process is still a critical field where AI can be incorporated into modern HRM (Benabou & Touhami, 2025). But, it does not mean that the availability of AI technologies ensures their effective organizational adoption. Pan et al. (2022) identified that technological complexity could limit the use of AI in recruitment, while technological competence, and regulatory support could enable it. The results indicate that factors other than technology play a crucial role in successful adoption of AI, including the capabilities of the organization, readiness to implement AI, and the context in which it is applied.

AI is also changing the dynamics between recruiters and technology. AI is not intended to replace human recruiters but is more likely to supplement their decision-making capabilities and influence the way recruitment activities are conducted. Dutta and Adsule (2026) show that AI and generative AI are changing the way recruitment and selection processes are done while also retaining the necessity of human-to-machine interactions. They also highlight the evolving dynamics between people, processes, and artificial intelligence systems within the process of hiring. This is especially true for startups, where teams are smaller, resources are limited, organizational setups are constantly shifting, and talent needs are changing rapidly. While AI can offer scalable support in the processing of candidate information, startups must have the requisite technological and organizational strength to put to use the insights that AI can bring.

This study, therefore, defines the AI adoption in recruitment as the use of AI technologies in the recruitment process, including the use of AI for résumé screening, AI powered interactions with candidates, predictive analysis and recruitment automation. The applications may be used to enrich the information gathered, processed and analysed during the recruitment process, but the ultimate added value of AI insights depends on whether they are used to inform systematic and evidence-based recruitment decisions. This is the conceptual link to the next mediator variable to explore: Data driven decision making.

2.1 Data-Driven Decision-Making in Recruitment

Data driven decision making (DDDM) is defined as the process of using relevant data, analytical evidence and created insights to make decisions in an organisation that are not predominantly

based on intuition, personal experience, or subjective judgement. In Human Resource Management (HRM), the rise of workforce data and analytical technologies has generated a greater call to action to use evidence-based approaches in HRM. For example, people analytics refers to the process of collecting and analysing employee-related information in a systematic and efficient manner to gain insights that can inform organizational decisions and strategies (Knapp et al., 2020).

DDDM used in recruitment is the process of utilizing the information of candidates and analytical evidence to assist screening, shortlisting, assessment, and selection. While the professional judgment of recruiters will still be important, it is possible for the subjective assessment alone to lead to inconsistent evaluations of candidates. A data driven approach can be used in addition to professional expertise to gather systematically collected evidence of candidates' qualifications, competencies, experience and other job relevant aspects.

HR analytics has enhanced organisations' ability to evidence based decision making. HR analytics turns HR data into information to be acted on that can be used in talent acquisition and other HR-related activities. The Fourth Industrial Revolution has made data driven HRM more relevant, says Majam and Jarbandhan 2022, because HR organizations have access to more data pertaining to their employees and powerful analytical tools. As a result, HR is shifting from information management to analytical support in making organizational decisions.

When AI is used in the recruitment process, DDDM becomes more relevant. Comprehensive applicant data can be analyzed with AI technologies like résumé screening, predictive analytics, and applicant matching. But having analytical outputs do not naturally lead to data-driven decisions. Recruiters should understand and apply the information provided by AI, and weigh it against broader background and industry information. Therefore, in addition to technology, proper DDDM must be well prepared by organizations, with the ability to analyze, and utilize human judgment.

DDDM might be particularly valuable for startups, where recruitment may happen at a time when the organization is uncertain, not very specialized in HR, and the talent needs are constantly changing. Systematic use of candidate data can offer a systematic framework for the evaluation of applicants, which can help to mitigate informal or intuition-based hiring practices. But, data availability, analytical skill, and technological infrastructure could impact the use of such evidence by start-ups.

In this study, data driven decision making in recruitment is defined as the degree to which startups routinely apply data and the information derived from AI and analytics to support recruitment and selection decisions. DDM is in the middle of the suggested framework as it is the pathway through which information created by AI is converted into recruitment results and, eventually, quality of hire.

2.1 Quality of Hire

Quality of hire is the degree to which new hires perform as expected and are productive when hired. While metrics like time to hire and cost per hire capture the efficiency of the recruitment

process, quality of hire examines what value the recruitment process is generating. It thus assesses whether an organization has chosen people who can work effectively and contribute to the organizational goals. Quality of hire is considered critical during recruitment because hiring too for efficiency may fail to reflect the gains that may be squeezed out of the successful hires in future. (Dutta et al., 2023).

There are many dimensions to quality of hire and can measure it by factors including satisfaction with the person hired, employee contribution, competency achievement, person job fit, and hiring manager satisfaction after hiring. However, there is no single measure which can be used in all organisational settings. The International Organization for Standardization (ISO, 2018) acknowledges that organizations need to decide on suitable quality of hire metrics based on their context. Such a context approach is especially important in start-up organizations where staff are often expected to do more and deal with evolving circumstances quickly.

Person job fit, and person organization fit are also key things to consider when thinking about quality of hire. Shet and Nair (2023) propose a framework for the quality of hire from a person environment fit viewpoint and show the use of machine learning methods for supporting employee selection based on various person environment fit aspects. Suitability is not just about a candidate's qualifications and experience; it also involves assessing how well the candidate's skills and attributes align with the requirements of the role and the organizational culture.

Another aspect of quality of hire is linking hiring decisions to employee and organizational results. The strategic value of the recruitment is realised when the right candidates are selected who possess the required skills and output when appointed. This focus on outcomes following the hire is noted by Dutta and Vedak (2023) who emphasise the employee's performance and longer-term employment outcomes. Quality of hire can then be used to tell whether recruitment initiatives are creating the desired employee or simply being effective and filling positions.

For startups, it's especially crucial, as hiring the wrong person or people can have a disproportionately negative impact on a smaller team and tighter budget. Therefore, hiring the right employees, a fit person, and a person who is adaptable to the job is of great importance to the success of an organization and its development. Therefore, the definition of quality of hire used in this study is the degree of employees' demonstration of the competencies, job fit and adaptability, and the resulting performance of those who are newly hired by startups that fulfil the organizational expectations. In the proposed model, the quality of hire is the main recruitment result that can be measured by the effectiveness of AI adoption and data-driven business decisions.

2.3 AI Adoption in Recruitment and Data-Driven Decision-Making

As Artificial Intelligence (AI) becomes more common in the recruitment process, it is not only changing the way recruitment activities are conducted, but it is also revolutionizing the way hiring decisions are made. In conventional recruitment, recruiters' experience, professional judgement and interpretation of the information of candidates are frequently relied upon when making a recruitment decision. Although human judgment is crucial, AI integration in the

recruitment process boosts the ability of organizations to gather, process, and analyze vast amounts of applicant data. Machine learning and natural language processing, predictive analytics, and applicant tracking systems are all technologies that can revolutionize the way candidate information is used to inform evidence-based recruitment decisions (Madanchian, 2024).

One of the most important ways that AI helps with data-driven decision making is its ability to convert various candidate data into information that can be easily analyzed and compared. AI tools can be used to analyse candidate-related data such as their resumes, application information, assessment scores, competencies, and more, to uncover patterns that might not be apparent in a manual review. Talent Analytics using AI can thus provide actionable insights from vast amount of HR data and be applied in the evaluation and selection of candidates (Qin et al., 2023). It's a significant step away from gathering data about candidates, and towards systematically using it for hiring decisions.

Purohit and Banerjee (2025) also showcase the link between AI usage and data-informed hiring decisions. They highlight the importance of combining data with AI based automation in recruitment for data driven decision making. AI can structure candidate data, facilitate comparisons, and offer analytical insights to recruiters. In this way, AI's impact goes beyond mere automation of repetitive hiring tasks to bolster the information base that drives hiring decisions.

This connection has been supported by recent evidence. In their systematic review on AI in HR decision making (Amanullah et al., 2026), the authors are clear that modern AI tools are transforming HR decision making by leveraging predictive analytics, personalisation, and data analysis. Within the HR domain, recruitment has been recognized as a critical area where advanced technologies such as machine learning, natural language processing, generative AI, and advanced analytics can play a significant role in aiding advanced decision making. But AI-assisted decision-making with the right amount of human touch, transparency and interpretation, not blindly following AI recommendations, is essential to make good decisions.

For startups, in particular, recruitment decisions are often made when the business is under-resourced, HR department is not fully staffed, the roles keep changing and the future is uncertain. By managing candidate information and offering analytical evidence, AI can offer a more organized and structured informational base for recruitment, which can be valuable for startups. These features allow business leaders to augment their own judgment with AI-driven data and insights and still use their own judgment to put the pieces together. The increased use of AI technologies in recruitment is therefore likely to further drive startups' dependence on data and analysis from candidates when making employment decisions. The technology enablement of AI allows for the creation, processing and use of recruitment data to support data driven decision making.

Given the above theoretical analysis and empirical findings, the following statement is advanced:

H1: Artificial Intelligence adoption in recruitment positively influences data-driven decision-making in startups.

2.4 Data-Driven Decision-Making and Quality of Hire

Data driven decision making (DDDM) can have a great impact on the quality of the recruitment outcome as it can be a systematic and evidence-based base for assessing candidates. Traditional recruitment decisions have been founded on a significant amount of subjective assessment and intuition for applicants, and experience of the recruiters. While professional judgment is still important, intuition on its own could lead to inconsistencies and cognitive bias. The evidence-based approaches aim to improve the quality of decision-making through the use of reliable information and critical professional judgement and not based on personal impressions.

In recruitment, DDDM facilitates the combination of data from resumes, structured evaluations, interviews, competency tests, ATS, and past employment experiences. Routine application of this type of evidence can help to streamline the process of comparing candidates to a set of job specifications, thereby minimizing the need for unstructured impressions. This applies especially to the quality of hire as the goal of selection is to find people who are likely to succeed once they have been hired. Evidence based selection practices, thus, give a better information base for matching candidate capabilities with job and organizational requirements.

When a company has performance and recruiting data from previous years, the connection between DDDM and the quality of their hires is significant. Linking information gathered before hiring with outcomes like the performance of employees, retention, competency development, and managerial assessment after the hire helps organizations determine which hiring factors correlate with successful hires. The process of recruiting can then be a learning experience in the organization, as data from the results of past hiring decisions help shape future candidate evaluations. This feedback allows quality of hire to become an actually measured recruitment outcome, rather than taken for granted.

There is some emerging empirical evidence in support of this relationship. In the study of recruitment in Indian product-based technology companies, Mallick et al. (2025) explored the potential of the use of predictive analytics and data driven decision making to enhance recruitment results such as quality of hire. Their results indicate that the systematic processing of recruitment data can help organizations to shift from a fragmented and subjective recruitment to more analytic decisions about which candidates to select. In a wider context, evidence-based HR practice also involves using sound evidence in a way that enhances the organization's decision-making processes, not just that of HR practitioners.

One of the reasons why DDDM might be useful in startups is that every appointment can have significant organizational implications. Startups often have slim teams, clear-cut duties, changing job demands, and know that they cannot afford an ill-fitted employee. That is, if you're going to be a startup recruiter, you should be able to have a more structured and defensible selection process by systematically analysing candidate competencies, assessment results, job requirements, and available historical information. Important, DDDM is not meant to always rely on quantitative evidence to make hiring decisions. Rather, evidence should be used in conjunction with recruiters' context-based understanding and professional judgment.

Therefore, the present study proposes that startups using systematically data collection and analytical evidence of candidates in the selection process will be able to select candidates with the competencies, characteristics and potential in accordance with the job and organizational requirements. Data driven decision making should, therefore, add to the quality of hire through the enhancement of information basis of candidate evaluation and selection.

Given all the above theoretical arguments and empirical evidence, the following proposition is advanced:

H2: Data-driven decision-making positively influences quality of hire in startups.

2.5 AI Adoption in Recruitment and Quality of Hire

Artificial Intelligence (AI) has significant potential to enhance the quality of candidate evaluation and selection in the recruitment process. Quality of hire is dependent upon the organization's capacity to recruit candidates with the characteristics of knowledge, skills, competencies, and job-related attributes that match the job requirements of a specific job. Artificial intelligence (AI) technologies can aid in this process by sifting through vast amounts of information in applications, uncovering patterns, and methodically comparing the profiles of applicants and job requirements (Campion & Campion, 2024).

A significant way in which AI can improve the quality of hire is by improving person job matching. Machine learning algorithms can review résumés, employment records, skill sets, and job descriptions to determine if a candidate is a good fit for a specific job opening. Gong et al. (2024) show how using AI for person job fit models can leverage candidates' career paths to enhance the match between candidates and jobs. These skills can help the recruiting team find applicants with the qualities that match the skills a candidate needs to succeed in the role.

AI can also enhance candidate evaluation by incorporating various sources of recruitment data. The recruitment systems using neural networks can integrate candidate data with past recruitment information, uncovering complicated connections among the attributes of applicants and the requirements of jobs (Wang et al., 2022). This enables the recruitment systems to go beyond the simple keyword matching toward a more holistic evaluation of the candidate's suitability. Likewise, machine learning techniques can be used to process other criterion-relevant candidate data from resumes and brief written responses, such as psychologically relevant attributes (Grunenberg et al., 2024). These are just a few examples of how AI can streamline the process of evaluating candidates on multiple dimensions.

But, adopting AI does not mean better quality hires. Data quality, model design, transparency, and the suitability of the criteria for candidate evaluation may all affect the recommendations provided by the algorithms. In their article, Chen et al. (2025) emphasize the need for transparency in explaining any disparities between algorithmic and human evaluations of person job fits. Hence, AI-based recommendations should be used in combination with expert judgment, not as a replacement for it. In turn, the impact of AI on quality of hire relies on the proper interpretation and use of analysis information in hiring decisions.

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They are especially important for startups, which often have more limited teams, changing job requirements and hybrid roles, that can have a bigger impact on bad hiring decisions. AI powered screening, predictive matching, and structured candidate assessment can offer a more structured foundation for startups to discover candidates that have competencies and traits aligned with jobs and organizational needs. As a result, the use of AI in hiring will likely lead to better quality hires by startup companies.

The following hypothesis is formed based on the prior theoretical arguments, and empirical evidence:

H3: Artificial Intelligence adoption in recruitment positively influences quality of hire in startups.

2.6 Mediating Role of Data-Driven Decision-Making

The use of Artificial Intelligence (AI) in recruitment can have a direct positive impact on recruitment results, the value of AI could be significantly shaped by the way organizations leverage the information produced by AI systems. While AI technologies can gather, process and analyse considerable candidate information, it is not enough to simply have the technology to make better hiring decisions. The significance of AI is in the value it brings to the organisation when it can provide outputs that are turned into evidence for action, and embedded into the recruitment process in an effective and systematic way. Thus, data driven decision making (DDDM) becomes an important explanatory mechanism that connects the use of AI in the recruitment process with the quality of hire.

AI tools for recruitment, such as automated résumé screening, predictive analytics, candidate-matching algorithms, and recruitment automation, give recruiters structured data about candidate capabilities and suitability. Purohit and Banerjee (2025) highlight the critical role of integrating high-quality data and employing AI-driven recruitment automation to enable data-informed hiring decisions. Likewise, a recent systematic evidence review reveals that AI is transforming HR decision making, boosting predictive and analytical capabilities in key HR processes, such as recruitment (Amanullah et al., 2026). Therefore, by adopting AI, recruitment decisions can be increasingly made on the basis of evidence, creating the technological and informational infrastructure.

DDDM, in turn, offers the means by which these technological capabilities can shape quality of hire. In addition to relying on intuition, recruiters can now logically integrate candidate data, assessment scores, compatibility predictions and previous recruitment data into selection decisions in a systematic way. Analytical recruitment frameworks have proven the capabilities of machine learning and optimization algorithms to anticipate recruitment success and to make better hiring and placement decisions (Pessach et al., 2020). Likewise, using machine learning for employee selection proves that analytics can help enhance person environment fit, a key component of quality of hire (Shet & Nair, 2023). These findings highlight the potential of AI beyond simply providing information for analysis, to being systematically integrated into recruitment decisions.

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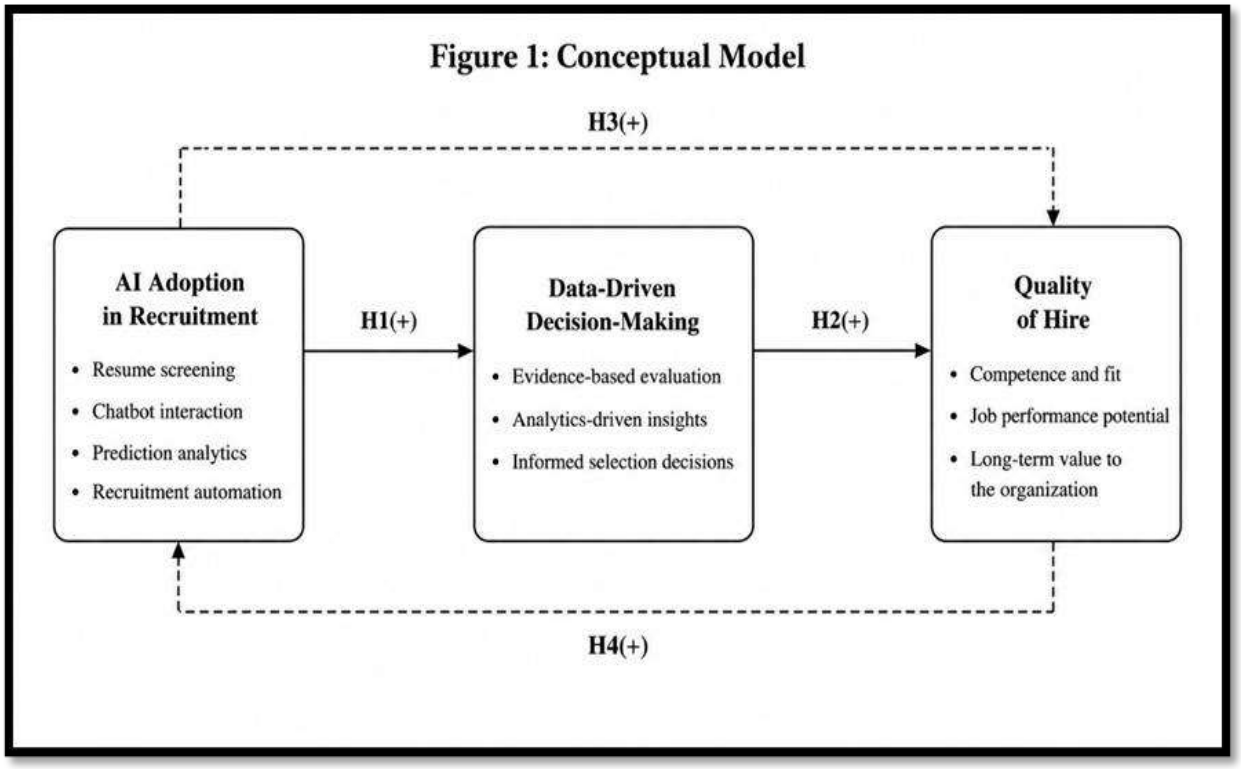
Mediating role of DDDM is more relevant for startups. In turn, the adoption of AI could help startups fill some of the gaps their HR teams encounter in terms of both specialization and resources. Conversely, AI implementation might help overcome some of the HR team's shortcomings within startups, such as limited experience and manpower. But the attributes brought by AI bring recruitment value only if the valuable insights from AI are put to effective use in the evaluation and selection of candidates. The use of AI can therefore enhance the evidence and systematic use of recruitment evidence, and this, in turn, can facilitate an informed process in identifying individuals with the right skills, traits and capabilities for the job and organisation.

The proposed mediation treatment is thus a sequential process. The integration of AI fortifies organizations' abilities to create and manage candidate data. This improved analytical ability promotes the use of data and evidence in hiring. The systematic use of these pieces of evidence can then benefit the evaluation and selection of candidates, leading to better quality hire. DDM thus offers one pathway in which the uptake of technology can be linked to actual recruitment results.

With this sequential logic, the present study theorizes that the impact of AI on the quality of hire can be direct, as well as indirect through data-driven hiring decisions. Based on this, the following hypothesis is put forward:

H4: Data-driven decision-making mediates the relationship between Artificial Intelligence adoption in recruitment and quality of hire in startups.

The Conceptual Model:



III. RESEARCH GAP

The use of Artificial Intelligence (AI) in Human Resource Management (HRM) has sparked significant interest in the field and specifically focused on the use of AI in recruitment and selection. Previous research has examined how AI can be leveraged throughout the talent acquisition process, from candidate sourcing to screening resumes, assessing candidates, matching, and selecting (Albert, 2019). The organizational and contextual factors affecting organizational adoption of AI in employee recruitment have also been studied, revealing that organizational competence with the technology, perceived complexity of the technology, and environment can impact organizational adoption decisions (Pan et al., 2022). While these developments are significant, there are still critical areas that need improvement to bridge the gap in understanding the impact of AI in recruitment.

First, the current literature has largely focused on the adoption, use, and performance of AI tools in recruiting, with a lesser focus on how the adoption of AI can improve the overall recruitment decision-making process. Second, the existing literature has not been extensive enough to examine how the adoption of AI can positively impact the overall recruitment decision-making process, in detail. While AI implementation doesn't always ensure better hiring results. While AI technologies can create, organize, and analyze candidate-related information, the organizational value will still come down to how decision makers use and interpret the information generated as analysis. Incorporating high-quality data and AI-driven automation is indeed crucial for making data-driven recruitment decisions, as recent research has shown (Purohit & Banerjee, 2025). The journey of how information created by AI is translated into better hiring results, however, needs to be developed further conceptually.

Secondly, while data driven decision making (DDDM) has gained significant traction in HR analytics and evidence based HRM, its specific role as a process between the adoption of AI and the outcomes of the recruitment process has been comparatively less explored. AI can ingest large amounts of applicant data to produce predictive gain aha moments, while DDDM is the organizational method in which gain aha moments are actually used to make hiring decisions. Banerjee and Purohit (2025) show that while the adoption of technology and the decision-making process are closely linked, AI can be truly helpful in recruitment and high quality data can aid in making data-driven decisions. However, more theory is needed to explain if and how DDDM can be an intervening mechanism between the adoption of AI and better recruitment results.

Third, current studies and literature of the use of AI in recruitment often focus on the technology and process related outcomes, and quality of hire should be considered as a strategic recruitment outcome. Quality of hire goes beyond the efficiency and completion of the recruitment process to whether the worker selected has the competencies, adaptability, performance potential and person environment fit the organization has. In the realm of recruitment, Shet and Nair (2023) show how machine learning and HR analytics can play a role in multiple aspects of person environment fit in the employee selection process, establishing an important linkage between

analytical recruitment practices and quality of hire. But, more conceptual integration is required to better understand how AI adoption and data-informed hiring decisions work together to drive quality of hire.

Last but not least, there has been a relatively limited amount of research on startups in this body of research. Startups have unique aspects to them: limited resources, fewer people in the HR team, shifting job descriptions, rapid growth, and not having the ability to handle bad hires. The wise use of recruitment information from AI and the success of quality hires are truly significant. It is important to note that results from contexts in larger and/or established organizations might not fully capture the recruitment realities and information processing needs of startups.

The aim of the present study is to fill these gaps, creating an integrated conceptual framework that connects the introduction of AI in recruitment processes, data-driven decision making, and the quality of hire in startups. In particular, the framework states that DDDM is a "mediating mechanism" that can be used to link the use of AI to the quality of hire. This study thus shifts the focus from the question of whether or not organizations are using AI to the question of how technological capabilities linked to AI are being turned into improved hiring outcomes via evidence-based recruitment decisions. This mechanism-oriented view and the emphasis on quality of hire as a strategic outcome are therefore the core conceptual deliverables of the proposed framework, with the focus on the startup context.

IV. THEORETICAL FOUNDATION: INFORMATION PROCESSING THEORY

The proposed conceptual framework is based on the Information Processing Theory (IPT) which was developed by Galbraith (1973, 1974) and further developed by Tushman and Nadler (1978). IPT proposes that the uncertainty of an organization raises the amount of information that needs to be processed and that effectiveness requires that adequate capacity be built within the organization to gather, process, and use pertinent information (Galbraith, 1974; Tushman & Nadler, 1978).

IPT offers a suitable basis for clarifying these connections between AI's use in recruiting, data-driven decision making (DDDM), and quality of hire. There is a lot of uncertainty with recruitment since the organization has to assess multiple information from various candidates including their skills, competencies, experience, performance capabilities, and suitability for the job. It is especially important when starting a business, the job needs often change, the structure of the company is not well defined and hiring decisions can have a drastic impact on an individual.

IPT's view of AI is that it increases the information processing ability of the organization. With the help of AI applications like résumé screening, candidate interactions, predictive analytics, applicant matching, and recruitment automation, companies can gather, structure, and analyze massive amounts of candidate data. These features convert unstructured data into structured information for assessment of candidates.

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But simply having a better information processing ability doesn't necessarily mean that the hire is better. All information has to be dealt with systematically and used to inform recruitment decisions. DDM is thus the process by which information created by AI is translated into evidence-based candidate evaluation. In a systematic way, using all the candidate data and insights, organisations can enhance competency assessment, job fit assessment and informed selection, which boosts quality of hire.

IPT is also making the connection between AI adoption and quality of hire, as better information processing can lead to better candidate screening, matching, and assessment. Therefore, the framework suggests both direct and indirect pathway via DDDM. The application of IPT to the recruitment of startups brings a modern twist to the standard theory, in which AI has become an increasingly powerful tool for the way companies process and use information to make hiring decisions.

V. THEORETICAL IMPLICATIONS

The conceptual study of the present is added to the growing body of literature related to Artificial Intelligence (AI) in Human Resource Management (HRM) where AI in recruitment can be understood as Data Driven Decision Making (DDDM) and its relation with Quality of Hire (QOH). The framework does not assume that adopting AI will automatically lead to better recruitment results but instead makes DDDM an intervening mechanism. This approach builds on the existing body of research on AI in recruitment by moving the focus from the technology to the organizational processes that enable the value added by information produced by AI in recruitment.

The study also extends Information Processing Theory (IPT) to AI supported recruitment. As with IPT, AI adoption increases an organization's ability to collect, process and analyze candidate data during times of hiring uncertainty. But the framework argues that when analytical information is incorporated into evidence-based hiring decisions, then increased information processing capacity becomes valuable. Therefore, a technological information processing ability is linked with the quality of hire in DDDM. The framework also places IPT in the context of startups where job demands change, resources are limited and the demand for talent is unpredictable which results in a higher information processing demand. Hence, the study combines technology, decision making, and recruitment outcomes in a parsimonious theoretical model.

VI. PRACTICAL IMPLICATIONS

The proposed framework for startup founders, HR managers and recruitment practitioners: The first thing that needs to be done by the startup is to look at AI adoption not merely as the automation of recruitment activities. When investing in résumé screening software, AI chatbots,

predictive analytics, and automation in recruitment, there should be processes in place to help recruiters effectively interpret and utilize the information created by AI.

Second, startups need to focus on improving their data-driven recruitment capability, setting up proper selection criteria, building up of accurate candidate information, linking recruitment information with the outcomes after hire, and recruiters' analytical skills. AI generated recommendations are meant to be used in conjunction with human judgment. Algorithmic outputs should be considered in conjunction with the context information, which includes requirements of the job and the needs of the organization.

Lastly, groups ought to regularly audit AI facilitated choice suggestions with subsequent worker execution and person job fit. This feedback can be used to gauge whether the use of AI in recruitment aligns with improving the quality of hire or simply adds to the technological sophistication of the recruitment process.

VII. FUTURE RESEARCH

The suggested relationships need to be tested through an experiment. Future studies could validate the framework by analysing data collected from startup founders, HR managers, recruiters and talent acquisition professionals, and investigate the direct and indirect relationships with structural equation modelling. It would be particularly useful to do a longitudinal study, as the quality of hire manifests itself in the results after hire that can be seen over time.

Future studies could also investigate whether the proposed relationships differ based on the size of startups, developmental stage, industry, technological capability, or environmental uncertainty. A comparative analysis of startups and existing businesses could help clarify if the use of AI in information processing results in different recruitment outcomes in different contexts. Some of the other boundary conditions that can be explored by researchers include AI transparency, data quality, AI literacy of recruiters, and human oversight.

Finally, future research might widen the scope to include additional outcome measures like employee performance, retention, organization fit, and innovation while maintaining the current model as a learning lens to the effects of AI supported, data driven recruitment on quality of hire.

VIII. CONCLUSION

Artificial Intelligence revolutionizes Hiring by leveraging vast amounts of candidate data, automating hiring processes, and providing valuable insights through analytics to aid in hiring decisions. But using AI doesn't automatically mean you're going to achieve better recruitment results. The utility of AI hinges significantly on how organizations make sense of the AI-driven information and use it to make informed managerial choices. To tackle this problem, the current conceptual paper introduces a cohesive model that connects AI adoption in recruitment, data-based decision making to quality of hire in startup organizations.

The model is based on Information Processing Theory and views the use of AI in recruitment as an organizational information processing capability that helps startups to cope with the complexity and uncertainty of candidate assessment. AI resume screening, AI Chatbots, predictive analytics, and recruitment automation help companies more systematically gather, organize, and analyse recruitment-related data. Data driven decision making then acts as the bridge between these technological capabilities and evidence-based candidate assessments and selection decisions. Therefore, this study suggests that the use of AI has a direct and indirect impact on quality of hire via data driven decision making.

These connections are important in the start-up setting. The landscape of start-ups is often characterized by constrained resources, small HR teams, changing job needs and relatively low tolerance for bad hires. Keeping this bottom line in mind, AI and data-driven recruitment methods may be able to systematically find candidates who have the skills and abilities that align to your organization's needs while doing it better. Even so, technology should be a tool alongside the human decision-making process, especially if it requires interpretation in the context.

Overall, the paper is a significant addition to the literature on AI in recruitment, and in doing so it takes the step beyond whether or not organizations are adopting AI to what forms of AI adoption can lead to better quality hiring outcomes. The framework uses data driven decision making as the mediator to offer a theory-driven explanation of how technological capability can lead to the recruitment outcome in a focused manner. Empirical testing of the proposed relationships could also be used in the future to further our understanding of the application of AI in recruitment, while also providing evidence of the circumstances in which AI is used in decision making that leads to quality of hire in start-ups.

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Intellectual Honesty and Research Integrity Addressing scientific misconduct through fabrication, falsification and Plagiarism

[1]Ankita Rani Mishra, [2]Dr. Diptirekha Mohapatra
[1]Research Scholar, P.G. Department of Law, Sambalpur University
[2]Assistant Professor, P.G. Department of Law, Sambalpur University

***Abstract*—The principles of integrity and honesty in research provide the basis for the credibility, reliability and development of scientific research. Scientific misconduct such as fabrication, falsification and plagiarism (FFP) is a real threat to science damaging public trust, compromising evidence, and misleading people from within the scientific community. The paper reviews the concepts of intellectual honesty, research integrity, and scientific misconduct and highlights the three major types of misconduct, their ethical, academic and societal significance. It also explores the consequences of fabrication, falsification and plagiarism on the credibility of science, institutional legitimacy and people welfare and discusses about the regulatory regime under the University Grants Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations, 2018. Finally, the paper points to preventive measures and recommendations in order to encourage ethical research practices, reinforce responsible science and ethical scholarship in general, and cultivate a culture of integrity, transparency and accountability in scientific research.**

***Index Terms*—fabrication, falsification, plagiarism, research integrity, scientific misconduct, intellectual honesty, research.**

I. INTRODUCTION AND BACKGROUND

The scientific community has long been considered to be one of the more trustworthy sources of knowledge, innovation and solutions to complex societal problems. Whether it's medical advances, technological progress, or legal changes, environmental efforts, or other policy decisions, research is the foundation of evidence-based decision-making and public policy. However, the validity of research is not only contingent on the quality of its methodology, but also the ethical behaviour of researchers. Researchers have a responsibility to pursue the truth by following the highest standards of intellectual honesty and research integrity, which involve obtaining accurate,

transparent, reproducible, and unbiased results from research (National Academies of Sciences, Engineering, and Medicine (NASEM, 2017).

In recent decades, research integrity has become an increasingly important global issue with the dramatic growth of scientific publications, interdisciplinary research, competitive grant funding, and the digital dissemination of research products. New technology has given rise to new opportunities for innovation, but also new challenges for ethics, such as pressure to publish, more competition for academic recognition, and more opportunities for wrongdoing. The changes have raised concerns about the reliability and credibility of the scientific literature, leading to an increased focus on promoting responsible conduct in research (Steneck, 2006, World Conference on Research Integrity, 2022).

Intellectual Honesty is not just a matter of following institutional guidelines but also a moral obligation to be truthful, fair, objective and accountable in the process of research. Researchers must be intellectually honest by collecting, analysing, interpreting and reporting data without manipulation or misrepresentation. It also requires proper citation and attribution of the work of other scholars. The responsibility for maintaining research integrity is therefore a shared responsibility among researchers, research institutions, peer reviewers, journal editors, research funders and policymakers, who collectively help to ensure the credibility of research (Resnik, 2020).

Even with the presence of ethical guidelines and regulatory bodies, cases of scientific misconduct are still undermining trust in research. A number of well-known instances of falsified clinical trial data, misreported experimental results, and plagiarism have shown that unethical research activities have real world implications that can be devastating. Scientific misconduct can result in dissemination of false knowledge, waste of valuable public resources, compromise of patient safety, misguide of public policies based upon inaccurate evidence, and loss of trust in scientific institutions. The relevance of upholding high standards of research integrity was further accentuated by the COVID-19 pandemic, and the need to ensure that inaccurate and/or manipulated results could impact global health decisions with significant consequences (Horbach, 2020).

There are numerous unethical research practices, which are commonly agreed to be the most serious are fabrication, falsification and plagiarism, commonly known as FFP. Fabrication is the invention of data or research results; falsification is the manipulation of research materials, equipment, procedures, or data to alter or distort the findings of research; and plagiarism is the representation of the work of others as one's own. These practices are a fundamental violation of principles of honesty, transparency, accountability, and respect for intellectual property, and reduce the integrity of the scientific record (Office of Research Integrity [ORI], 2000). There has been growing attention in international organisations to the need for a harmonised approach to principles of responsible research conduct. Honesty, accountability, professional courtesy, transparency and stewardship are principles supporting ethical research that are highlighted in documents including the Singapore Statement on Research Integrity (2010), the European Code of Conduct for Research Integrity (2023) and the Montreal Statement on Research Integrity in

Cross-Boundary Research Collaborations (2013). Likewise, national regulations and funding bodies have established detailed policies covering ethical approval, data management, disclosure of conflicts of interest and investigation of complaints of research misconduct (ALLEA, 2023). The increasing importance of academic excellence, interdisciplinary research and university rankings in India have led to greater awareness of research ethics and academic integrity.

The University Grants Commission (UGC) has laid down comprehensive guidelines for ensuring academic honesty through the University Grants Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations, 2018, which specify the institutional procedures for detecting plagiarism, awareness programmes and disciplinary action. The regulations have been framed as per the policy of India, which aims to maintain the academic standards of India according to the internationally accepted principles of responsible research conduct and promote ethical research culture among the HEIs (University Grants Commission [UGC] 2018). The values of research integrity are not only about preventing the occurrence of research misconduct, but they are also underlying values of maintaining public trust in science, safeguarding the welfare of research participants, efficient use of research funding and enabling meaningful scientific progress. While misconduct harms the goals of reproducibility, transparency, and collaborative innovation, ethical research practices foster these goals and build trust in academic institutions. Ethics education, institutional accountability, mentorship, and the creation and maintenance of an academic culture that encourages, and is committed to, quality, transparency, and integrity, are needed as well as effective regulatory mechanisms, to encourage and promote intellectual honesty (NASEM, 2017; Resnik, 2020).

In this context, the present paper discusses the issue of scientific integrity and its linkage with intellectual integrity which is explored by discussing the concept of scientific misconduct with emphasis on fabrication, falsification and plagiarism. It also discusses the ethical, legal, academic and societal implications of such misconduct, examines current national and international approaches to regulation and outlines strategies to support the development of good practice in research. In this analysis, the paper aims to join the ongoing debate of fostering ethical scholarship and ensuring the integrity of scientific research in the current competitive and interconnected academic landscape.

II. DEFINING INTELLECTUAL HONESTY, RESEARCH INTEGRITY AND SCIENTIFIC MISCONDUCT

Intellectual integrity is an important ethical tenet, which demands that researchers seek to and communicate knowledge honestly, objectively, and transparently. It reflects a dedication to accuracy in collecting, analysing, interpreting and reporting research results and an appreciation of the work of others by giving proper credit and citing their work. Intellectual honesty is not just about following rules or regulations instated by institutions but about an individual's moral obligation to avoid bias, manipulation, selective reporting and misrepresentation at various stages of the research process. It requires that researchers present evidence without being selective in

what they present, even if the evidence doesn't support their hypothesis, expectations, or personal interests (Resnik, 2020).

It is not just about not plagiarizing or falsifying information, it is about being open to criticism, open to error and ready to change one's conclusions based on new evidence. Promoting an academic culture based on fairness, accountability and respect for the cumulative nature of scientific knowledge, therefore, is promoted by intellectual honesty. Because research depends on the power to verify, replicate and extend existing research, honesty in reporting is essential to the credibility and reliability of research results (National Academies of Sciences, Engineering, and Medicine [NASEM], 2017). Ethically, intellectual honesty helps to protect public trust in scientific institutions. Governments, judiciary, healthcare practices, technology and social welfare programmes are all affected by research. Misrepresentation of facts is not only a violation of scholarly integrity but can also have negative repercussions for society. Therefore, in all academic fields, intellectual integrity is considered an ethical duty and a professional ethical principle (Steneck, 2006).

Research Integrity: Research integrity is the application of ethical principles and professional standards for research that are considered necessary for perpetuation of research as a process conducted with responsibility, transparency and objectivity throughout its life cycle. It involves planning and conducting research, recording it, reviewing it, publishing it, disseminating it, and analysing it, in an honest, accountable, fair and respectful manner, taking care to research participants, colleagues and society. It is a positive approach to research that enhances the quality, reproducibility and trustworthiness of scientific knowledge (ALLEA, 2023). Research integrity is generally recognized internationally as the four principles elaborated in the Singapore Statement on Research Integrity and those are, “honesty in all aspects of research, accountability in conducting research, professional courtesy and fairness in collaboration, Good stewardship of research for others.” The principles highlighted the need for research integrity, which includes keeping good records, declaring conflicts of interest, providing full and objective reporting of research and giving credit to the work of others and previous researchers (World Conference on Research Integrity, 2010).

The European Code of Conduct for Research Integrity also builds on these principles, and outlines the following principles of responsible research: reliability, honesty, respect and accountability. The Code states that researchers are supposed to be methodologically sound, transparent in data management, ethical in the treatment of humans and animals, responsible as authors, and open in communicating research results. All these standards help to maintain the credibility of scientific publications and to build trust in academic institutions in scientific research (ALLEA, 2023).

In the Indian context, research integrity has gained significance in the field as now it is getting more institutional attention through several legislations and regulations like the University Grants Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations, 2018. The regulations urge higher learning institutions to implement tools and systems to tackle plagiarism, awareness campaigns, and disciplinary actions

and encourage ethical research among students, researchers, and teachers. The regulations are in line with the aim and vision of India to build a culture of responsible scholarship, which is in tune with the universally accepted research ethical norms (University Grants Commission (UGC, 2018).

Scientific Misconduct: Scientific misconduct is defined as knowingly or inadvertently committing acts of or allowing acts of scientific misconduct, which is defined as actions that are intentionally or recklessly undertaken that are contrary to scientific integrity or best practices. It includes any act of altering, concealing, misrepresenting or jeopardizing the validity of the research process and the reliability of scientific information. Scientific misconduct differs from honest mistakes or methodological limitations, or even differing interpretations of the scientific facts, in that it is deliberate deception or a substantial deviation from accepted scientific practices that ultimately leads to misleading or fraudulent results (ORI, 2000).

The definition of scientific misconduct used by the United States Office of Research Integrity (ORI) was one of the most widely accepted definitions of FFP and that is the fabrication, falsification or plagiarism in proposing, performing, reviewing, or reporting research.

- Fabrication: To make up data or results and record or report them;
- Falsification: To manipulate research materials, equipment, processes, or data such that the research record no longer accurately reflects the actual findings;
- Plagiarism: To record or report another person's ideas, processes, results, or words without giving appropriate credit (ORI, 2000).

Scientific misconduct is very much distinct from research error or negligence. A genuine error caused by an error of some equipment, computational error or some unexpected limit in methodology is not considered misconduct, as long as it is admitted and corrected with good faith. Likewise, when there is a genuine difference of opinion or interpretation of data, or methodological approach, it is not deemed to be misconduct. The hallmark of scientific misconduct is the intentional deception, recklessness with regard to research integrity, or conscious misrepresentation of evidence (NASEM, 2017).

The repercussions of scientific misconduct are far-reaching beyond the individual scientist. These are all potential consequences of fraudulent research which can lead to misguiding future research, the loss of public money, compromising safety for patients, manipulating governmental policy, tarnishing reputations and destroying public faith in science. As a result, a number of legal measures and institutional frameworks have been put in place to investigate and punish scientific misconduct and to encourage responsible conduct of research, by governments, funding agencies, universities, publishers, and international organisations. These are steps to upholding scientific integrity, knowing that in today's knowledge-driven society, the social value and credibility of scientific research is critical (Resnik, 2020; Steneck, 2006).

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III. FORMS OF SCIENTIFIC MISCONDUCT DEFINED

While there are many forms of misconduct in research, there is international agreement that the three main forms are fabrication, falsification and plagiarism (also known as "FFP"). FFP is more than academic ethics. Research results are often used to guide decisions by the courts, to inform changes in laws, to direct medical and health care interventions, to shape educational programs, innovative approaches in industry, and environmental management. This can lead to wrong public policy, unsafe medical care, monetary losses, harm to institutions' reputations and loss of trust in science. Multiple examples have been reported in the public press such as fabricated stem-cell studies, faked trials on vaccines, and diverse plagiarism scandals, which have shown that even a single case of misconduct can have international consequences and erode trust in scientific institutions (Resnik, 2020; Steneck, 2006).

Given these threats, the international bodies World Conference on Research Integrity, Committee on Publication Ethics (COPE), European Federation of Academies of Sciences and Humanities (ALLEA) and International Committee of Medical Journal Editors (ICMJE) have established guidelines on ethical conduct in research, which demand that researchers be honest, transparent, accountable and responsible in their research. All of these frameworks share a focus on ethical behaviour in all stages of scientific research, from formulating a hypothesis to research results being published and disseminated, as well as the importance of technical competence (ALLEA, 2023; COPE, 2019).

The three major types of scientific misconduct that are fabricated, falsified and plagiarized are described in the following sections, along with their distinguishing features, their apparent forms, their consequences, and the ethical considerations.

1.Fabrication of Data

Fabrication is considered one of the most egregious practices of scientific misconduct since it involves the creation of research data, observations, experiments, participants, or results that did not actually occur. The researcher makes up information instead of collecting evidence through scientific investigation and presents the made-up information as scientifically collected evidence. This behaviour undermines intellectual honesty and compromises the trustworthiness of scientific research since data that has been invented cannot be confirmed or reproduced independently (Office of Research Integrity [ORI] 2000).

The Office of Research Integrity (ORI) defines fabrication as "making up data or results and recording or reporting them" (ORI, 2000). Fabrication is defined as deliberate deception, as opposed to methodological errors or statistical error. It is an intentional change of fictional evidence for real evidence, leading to the misleading of readers, reviewers, funding agencies, policy makers, and other researchers. As science progresses, invented results taint the scientific record and can potentially mislead future research for a long time (National Academies of Sciences, Engineering, and Medicine [NASEM] 2017).

Fabrication can happen at any and all points in the research process. Researchers can make up observations, manipulate answers to surveys, develop clinical trial subjects that never existed, conduct lab experiments for which there are no data, or present statistical calculations from non-existent data sets. In qualitative research, fabrication can include making up interview protocols, focus group discussions, field observations, or documents. In legal and social science research, for example, false case studies or surveys can lead to false conclusions that can drive policy recommendations and legal debates (Shamoo & Resnik, 2022). There are a number of reasons for fabrication. Today's academic landscape is clearly marked by a high level of competition for grants, academic advancement, institutional prestige, and publication in prestigious journals. The much-decried 'publish or perish' culture can lead to a lot of pressure for researchers to generate positive and statistically significant results in a short time. Sometimes researchers may be pressured, by supervision, poor institutional control, monetary rewards or fear of failure to publish work that falls short to publish false or negative results. While pressures might be the cause for misconduct, they are not morally legitimate to intentionally deceive (Fanelli, 2009).

The most famous example of fabrication is the case of South Korean stem-cell researcher Hwang Woo-suk who claimed he had successfully cloned human embryonic stem cells. Published in Science in 2004 and 2005, his research attracted worldwide acclaim and was hailed as a revolutionary breakthrough in regenerative medicine. Further inquiries, however, were to show that much of the information reported had been fabricated and manipulated. The scandal led to the retracted papers being published, the dismissal of the researcher, criminal charges and severe loss of public trust in stem-cell research. The case is a classic illustration of how 'research can be invented to shape a fact' and how a lot of money can be squandered on the process (Cyranoski, 2006). The principle of reproducibility is also violated by fabrication, a key aspect of scientific research. Any real scientific findings should be replicable by other scientists. No one ever observed the facts underlying fabricated findings, so they cannot be replicated. This means that other scientists can invest significant time, money, and effort trying to replicate the fictional findings. (NASEM, 2017).

2. Falsification of Data

Falsification starts with real research, but the researchers manipulate the research process or results, in a deliberate way, to obtain a desired outcome, whereas fabrication involves making up data entirely. These actions undermine the validity, credibility and replicability of scientific information and deceive others, thus undermining the principles of scientific research integrity and intellectual honesty (Office of Research Integrity [ORI], 2000).

According to the United States Office of Research Integrity, "falsification" is defined as "manipulating research materials, equipment or processes; or changing or omitting data or results such that the research is not accurately represented in the research record" (ORI, 2000). This definition reinforces the idea that falsification can involve any kind of manipulation of the research record, not just numbers. This can happen during any phase of the research process, from design, to data collection, statistics, image processing, finding interpretation, or even publication. A

falsification is not an honest error in science or due to flaws in the methodology. Research is always subject to uncertainties and investigators may occasionally find that equipment breaks, calculations are wrong, samples are mis collected or misinterpreted. The shortcomings are not considered as misconduct if they are recognized and rectified good faith. (NASEM, 2017).

Depending on the field and approach, falsification can take many different forms. In quantitative research, this can include changing numerical data to maximize the significance of the data, selectively omitting outliers that do not have scientific basis, tampering with the size of the samples, omitting data that is not convenient, adjusting variables to get desirable results or omitting outlier data that does not fit with the other data. Researchers can also use the statistical methods inappropriately by implementing p-hacking, which involves performing several statistical analyses with no a priori hypothesis in mind until results that are statistically significant come back. Likewise, the HARKing phenomenon (Hypothesizing After the Results are Known) is when researchers propose a hypothesis after analyzing the results as if it had been formulated beforehand, leading readers to believe that the results were valid or not (John, Loewenstein & Prelec, 2012).

In qualitative research, falsification can include selectively characterizing responses given during interviews, deleting information that contradicts the conclusions of the study, changing information that exists in the field notes, or changing information that appears in documents. For instance, in socio-legal studies, a researcher may want to deliberately overlook judicial rulings or legislative documents which are contrary to the main thesis of the study. While qualitative research is always interpretive, the researcher should always be faithful to the evidence and avoid manipulating it to make it more consistent with a preferred story (Shamoo & Resnik, 2022).

Pressure is a major contributor to falsification, one of the main factors being the pressure on academic performance indicators in today's society. The number of publications, the citation indexes, research grants and the positions of the institution in the rankings are increasingly used to assess scholars at universities and research institutions. The "publish or perish" ethic could encourage researchers to come up with new, significant or positive results even if they are not supported by the evidence. Other factors in competitive funding, career advancement, tenure, and professional recognition also might create the "Pressure to Bias Research Results" (Fanelli, 2009; Steneck, 2006).

There are a number of well-known examples of the effects of falsification. In one of the biggest identified cases, Yoshitaka Fujii, the Japanese anaesthesiologist whose studies were discovered to contain copious amounts of data manipulation and falsification. Investigations found statistical irregularities in a large number of publications, and led to the retraction of over 180 scientific articles, one of the highest numbers of retractions ever attributed to a single researcher. The case demonstrated the need to examine research data statistically, to monitor them institutionally, and to hold the journal accountable for their accurate representation before they become part of the medical literature (Carlisle, 2012).

Another interesting case is the German anaesthesiologist Joachim Boldt, whose work on intravenous fluid and electrolyte therapy had to be retracted due to research falsification, data

irregularities and ethical violations. The misconduct involved evidence used in anaesthesiology and intensive care medicine, and reshaping of treatment recommendations, which were based on falsified studies, which makes the clinicians and researchers reconsider their treatment recommendations. The Boldt case is a good example of how a study with serious research misconduct can lead to the rejection of evidence-based medicine and the loss of confidence in published scientific literature (Kranke, Apfel, & Roewer, 2011).

3. Plagiarism

Plagiarism might be the most prevalent and serious type of scientific cheating, since it is the theft of another individual's intellectual property without proper citation. Plagiarism differs from fabrication or falsification, which involve altering data about the research, by involving an unethical presentation of another person's idea, words, data or creative expression(s) as one's own. This is a breach of the standards for responsible research that uphold intellectual honesty, fairness and accountability. Researchers have a moral responsibility to give credit to other people's work, to cite and reference works that lead to their own, and to cite and reference other people's work that they build on (National Academies of Sciences, Engineering, and Medicine (NASEM, 2017). Plagiarism is defined by the United States Office of Research Integrity (ORI) as "The appropriation of another person's ideas, processes, results, or words without giving credit to the originator" (ORI 2000). Plagiarism too, according to the Committee on Publication Ethics (COPE) is any presentation of another party's work as if it were one's own, whether deliberate or inadvertent (Committee on Publication Ethics [COPE], 2019).

How someone uses another person's work can be different types of plagiarism. Copying from a published or unpublished source of text without quotation marks or proper citations is called direct plagiarism. It's the simplest kind of plagiarism and is likely to be considered a conscious attempt to cheat. This form of plagiarism is evident and can have severe academic and professional ramifications (Roig, 2015).

Another type is called mosaic or patchwork plagiarism, where a researcher quotes from more than one source, but changes the wording of the quotation and does not cite the original sources. There may be some word changes but the substance of the ideas is largely lifted. Mosaic plagiarism is more difficult to detect than exact plagiarism, and can mislead readers of the plagiarized work as to its originality (Pecorari, 2015).

Plagiarizing by paraphrasing takes place when an author restates the ideas of another person in his or her own words without giving credit to the other writer. A paraphrase must not only be a substantial restatement of the original text but it must also be properly referenced to the original text. If the ideas are borrowed, it's not original work, just a few words and sentence structure changed. As a result, even when a quote does not occur in the text, it is still necessary to cite the source (Shamoo & Resnik, 2022).

Self-plagiarism is another form of plagiarism that has become very serious; it is when researchers copy large sections of their previously published work without proper attribution or citation. The material originally written by the same author may be presented as if it were entirely new research,

which may lead the editors, reviewers, funding agencies and readers to question the originality of the publication. Duplication of publications, duplication of publications of any sections, and plagiarism of text, tables and figures without citations are common self-plagiarism practices (Roig, 2015).

Idea plagiarism occurs when you take another researcher's ideas, hypotheses, methodology, interpretations or research designs without giving proper credit. Unlike with textual plagiarism, idea plagiarism can take place even if the words were not copied. Ethical research involves giving credit to the original source of ideas, especially if the ideas have in some way driven the research being done, since intellectual contributions do not stand alone, but are also represented in other ways such as in written form (Fishman, 2009).

Plagiarism has been an issue in India which has been addressed by the University Grants Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations, 2018. Institutions of higher learning and universities should implement measures to detect plagiarism, establish Academic Integrity Panels, awareness programmes and provide a ranking of penalties based on the percentage of plagiarized content. To prevent plagiarism, a combination of individual moral responsibility and institutional efforts is needed. On a practical level, researchers need to safeguard their research by keeping careful research notes, learning how to paraphrase, citing all the sources, using quotation marks correctly, and following the reference styles (UGC, 2018). Consequences of Scientific Misconduct

If the integrity is lost, by fabrication, falsification or plagiarism, the impact extends beyond the person involved. The consequences on society as a whole are significant both socially, economically and legally when research is flawed, as it can have an impact on medical treatments, court decisions, public policies and innovations. This has led to an even stricter approach by international organizations and regulatory bodies to discourage scientific misconduct and to promote research integrity (NASEM, 2017; Resnik, 2020).

Fabrication and falsification directly distort the authenticity of the scientific record by providing false or manipulated evidence in the scientific record. These false discoveries can lead to failure in future research, by forcing repetition of flawed experiments and waste of funding. The falsification or fabrication of data can result in wrong clinical guidelines, unsafe treatment options, slow scientific advances, and endanger patient safety in fields like medicine and public health. (Steneck, 2006; Shamoo & Resnik, 2022).

While plagiarism differs from fabrication and falsification, the implications are serious nonetheless, as plagiarism is an offence against intellectual integrity and an unfair claim on the credit of the original author(s). A researcher who has been caught plagiarizing can have their manuscript rejected, article removed, lose credibility, be suspended from academic programmes, fired from their jobs, research grants rescinded, and be marred for years. Plagiarism detection software and strict policies are increasingly being used by academic institutions and publishers to detect and deal with plagiarism pre-publication (Committee on Publication Ethics [COPE], 2019; Pecorari, 2015).

Plagiarism is mentioned and regulated specifically under the University Grants Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations, 2018 in India. Academic dishonesty is penalized according to Regulation 12 which uses a percentage of similarity to determine the extent of the dishonesty. If the similarity is up to 10% (Level 0) it is considered minor similarity and no penalty is given. If the thesis is above 10% to 40% (Level 1), it needs to be revised or withdrawn. In Level 2 (40-60%) the student faces more severe penalties, which may include debarment from submitting revised work for a defined period, and in Level 3 (more than 60%) may result in cancellation of registration for the student or other harsh disciplinary measures for faculty and researchers.

The Regulations also stipulate penalties shall be imposed only following due inquiry, application of principles of natural justice and exhaustion of appellate remedies. The provisions are in keeping with the spirit of upholding academic integrity and a high standard of research ethics in higher educational institutions in India. (ALLEA, 2023; NASEM, 2017).

IV. CONCLUSION

One of most pertinent elements of prevention is to inculcate a culture of honesty, transparency, accountability and moral responsibility (NASEM, 2017). Establishing clear and regular policies for reporting and the investigation of misconduct is also essential, including those that provide for fairness, confidentiality and due process in all cases. Plagiarism software (e.g., Turnitin and iThenticate), a required data management plan, strict peer review, research audits, and open science all put the screws into fabrication, falsification and plagiarism.

Moreover, the mentors and supervisors have a large contribution in guiding and supervising the new and yound researchers to executing their research in an ethical (ALLEA, 2023; Shamoo & Resnik, 2022). National policies such as the Regulations, 2018 of the University Grants Commission (UGC) of India, contribute to academic integrity by encouraging awareness campaigns, ensuring compliance, and implementing fair disciplinary measures, thereby preserving the trust of the public and facilitating the trusted and reliable conduct of research and responsible work practices that benefit society (UGC, 2018). The integrity, trustworthiness and advancement of science depend on intellectual honesty. Fabrication, falsification and falsification or theft of data by researchers not only infringe upon ethical codes but also violate public trust, consume precious resources and actively impede human progress. It's a shared responsibility among researchers, research institutions, publishers, funders and regulators. Institutions should introduce regular ethics training to ensure its protection, promote transparent data policies, and take a firm stance against misconduct by enforcing rigorous action against it. This means for researchers, that they retain perfect records and they are able to cite others perfectly according to international standards of ethics. A combination of continuous awareness programs, severe peer review and compliance to requirements such as the UGC Regulations will help foster an environment of accountability for research. Only in this way will public trust be gained, real breakthroughs will be achieved in science and research will continue to be useful to the world.

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Customer Perception and Satisfaction Towards Surplus Retailed Items

[1]Lindy Mae A. Catam-isan, [2]Jecel Mae S. Navarro, [3]Arnold P. Tanio
[1,2,3]Student Researcher, Bachelor of Science in Entrepreneurship IBA College of Mindanao, Inc Valencia City, Bukidnon, Philippines

***Abstract*—This study entitled Customer Perception and Satisfaction Towards Surplus Retailed Items, was conducted by Lindy Mae A. Catam-isan, Jecel Mae S. Navarro, and Arnold P. Tanio, of IBA College of Mindanao Inc., Bachelor of Science in Entrepreneurship, School Year 2025-2026. Study sought to determine the level of customer perception towards Korean and Japanese surplus retailed items in terms of product quality, product availability, and product affordability, and to determine the level of customer satisfaction towards Korean and Japanese surplus retailed items in terms of purchase experience, repurchase intention, and recommendation. It also sought to examine the significant relationship between customer perception, and customer satisfaction. Conducted under the guidance of James Lloyd N. Gabitano, MBM, MPSM, CSO2, adviser. The study is a descriptive-correlational research design that uses a researcher made survey questionnaires with 4-point likert scale was validated and underwent reliability testing (Cronbach's Alpha = 0.85). Data were collected from one hundred fifty (150) conveniently selected respondents who were customers of purposively selected six (6) Korean and Japanese surplus stores in Valencia City, Bukidnon. The level of customer perception and customer satisfaction was identified using mean and standard deviation, relationship between customer perception and customer satisfaction was identified using Pearson's r. Finding revealed that customer perception towards Korean and Japanese surplus retailed items was very positive level. In terms of product quality level, the overall mean was 3.37 (SD=0.68) interpreted as Very Positive, where highest indicator was "The surplus items I purchase are generally in satisfactory condition" with a mean of 3.44 (SD=0.66), the lowest was "The products demonstrate a reasonable level of durability despite prior use" with a mean of 3.23 (SD=0.68) interpreted as Positive. For product availability, overall mean was 3.29 (SD=0.66) interpreted as Very Positive, with the highest indicator "The store provides sufficient options to accommodate different customers" with a mean of 3.36 (SD=0.69) and the lowest being "The store consistently provides the items I intend to purchase" with a mean of 3.21 (SD=0.73) interpreted as Positive. For product affordability, overall mean was 3.29 (SD=0.69) interpreted as Very Positive, where the highest indicators "The pricing of products is generally within my financial capacity" with (SD= 0.67) and "The cost of**

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products significantly affects my decision to purchase" (SD= 0.73) both has mean of 3.33, while the lowest indicator was "The pricing of products is reasonable in relation to their quality" with a mean of 3.21 (SD=0.68) interpreted as Positive. The customer satisfaction towards surplus retailed items was generally satisfactory. For the level of purchase experience, the overall mean was 3.25 (SD=0.67) interpreted as Highly Satisfied, with the highest indicator "I find the experience of shopping for surplus item to be enjoyable" with a mean of 3.38 (SD=0.68) interpreted as highly satisfied, the lowest was "Store personnel are approachable and provide adequate assistance" with a mean of 3.14 (SD=0.66) interpreted as Satisfied. For repurchase intention level, the overall mean was 3.17 (SD=0.70) interpreted as Satisfied. For the level in regards to recommendation, respondents obtained an overall satisfied level with an overall mean of 3.23 (SD= 0.76). The study also revealed a significant positive relationship between customer perception and customer satisfaction, with an overall r-value of 0.713 and p-value of 0.001, indicating that improved customer perception contributes to higher customer satisfaction. Therefore, hypothesis was rejected. Study concluded that customers have a very positive perception towards Korean and Japanese surplus retailed items in terms of product quality, product availability, and product affordability. Customers were generally satisfied with their purchase experience, repurchase intention, and recommendation of surplus retailed items. The findings further revealed that customer perception has a significant positive relationship with customer satisfaction, indicating favorable perceptions of surplus retailed items contribute to higher customer satisfaction.

***Index Terms*—Customer Perception, Customer Satisfaction, Product Quality, Product Affordability, Product Availability, Korean and Japanese Surplus Stores.**

I. INTRODUCTION

Small businesses play an important role in the local economy, especially in developing cities like Valencia City, Bukidnon. Korean and Japanese Surplus are common retail businesses that provide goods to the community and serve as a source of income for many families. Surplus retail stores have become popular among consumers, offering different quality products at affordable prices.

Despite the popularity of Korean and Japanese surplus items in Valencia City, Bukidnon, there is limited information on how customers perceive Korean and Japanese surplus items and how satisfied the customers with the products and items offered by these surplus retail stores. Customers have different intent in purchasing Korean and Japanese surplus items. Some may purchase surplus items because they are affordable and in good quality, but some customers may also have different issues related to items or product quality. Store owners find it difficult to determine whether customers are satisfied or which part of their business needs improvement, which is why there is a need for a measurable data about these factors.

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This study aimed to provide systematic evidence for the level of customer satisfaction in Japanese and Korean surplus stores in Valencia City, Bukidnon. Surplus items are popular because of affordable and quality products and items, but there is limited quantitative information on customer satisfaction. This study will identify the factors that most influence satisfaction and help store owners understand their customers' needs and expectations.

II. LITERATURE REVIEW

Customer perception is shaped by how consumers evaluate the overall value and performance of products in relation to their expectations. Rather than considering product attributes independently, customers tend to form an overall judgment based on whether a product is reliable, reasonably priced, accessible, and capable of providing the benefits they seek. Tulcanaza-Prieto et al. (2022) found that positive customer perceptions contribute to satisfaction and loyalty, while Keshavarz and Jamshidi (2018) emphasized that perceived value and satisfaction are important mechanisms through which customers develop favorable behavioral responses. This suggests that customer perception is closely connected to the value customers perceive from their overall purchasing experience.

Accessibility also forms part of this value evaluation. Ndruru et al. (2023) found that product availability contributes to customer satisfaction by allowing retailers to meet consumer demand, while Rajavi and Modaresi (2024) showed that inventory levels can positively influence consumer perceptions. These findings suggest that favorable perceptions may be difficult to sustain when customers cannot access the products they want, even when the products are perceived as affordable and of acceptable quality. Thus, quality, affordability, and availability can collectively influence whether customers perceive a product as providing satisfactory value.

This relationship is particularly relevant in surplus retailing, where customers may evaluate products based on their condition, usefulness, price, and availability rather than relying solely on brand reputation. Gok et al. (2019) emphasized that customers' understanding of product information and perceived value can influence satisfaction, while Graciola et al. (2018) found that favorable price perceptions can strengthen repurchase intentions. Therefore, when customers perceive surplus items as reasonably priced, sufficiently useful or reliable, and accessible, these perceptions may contribute to a more favorable purchasing experience and greater satisfaction.

III. MATERIALS AND METHOD

Research Design

This study employed descriptive correlational. The descriptive design was used to describe the level of customer perception and customer satisfaction towards retailed items in the Korean and Japanese surplus stores in Valencia City, Bukidnon. Specifically, the first and second research objectives are both descriptive because they aimed to determine the level of customer perception on retail items in terms of product quality, product availability and product affordability, as well as the level of

customer satisfaction in terms of purchase experience, repurchase intention and recommendation. These factors focus on describing the existing conditions and practices of the respondents.

The correlation was used to examine the relationship between the variables in the study. The third research question, which asks whether there is a significant relationship between customer perception and customer satisfaction, it involves numerical data and statistical analysis. This study uses measurable data collected from the respondents to determine whether customer perception towards Korean and Japanese retail items significantly influences customer satisfaction. Therefore, this study is descriptive correlational approaches to both describe the variables and analyze the relationship between them.

Participants/Respondents

The respondents of the study consisted of Korean and Japanese surplus customers in Valencia City who were purchasing items at specific surplus retail stores during the data gathering to the following stores namely: AMAREY Japan Surplus, EZEN Premium Japan Surplus, Is Surplasan , PiaMia Japan Surplus, VALPER Japan Surplus, and lastly, Zean Japan Surplus. The total sample size is one-hundred fifty (150). There are six (6) Korean and Japanese surplus stores included in this study.

Data Gathering Procedures

The data gathering procedure was conducted in a systematic and organized manner. First, the researchers secured a formal approval from the research adviser and the letter of consent from the store managers of surplus retailed items in Valencia City, Bukidnon. Once approval is granted, the researchers identified the six Korean and Japanese surplus stores. After identifying the qualified respondents, the researchers personally administered the questionnaires to each of the customers who are purchasing in specific surplus stores. This personal administration allowed the researchers to clearly explain the purpose of the study, provide instructions, and address any questions or clarifications from the respondents. It also helps ensure the accuracy of responses and guarantees a 100% retrieval rate of the completed questionnaires. After all responses are collected, the researchers organized and prepare the data for analysis.

Statistical analysis

To determine the level of customer perception and customer satisfaction, the Weighted Mean was calculated for each indicator. The result of each average was interpreted using a four- point Likert scale. The Standard Deviation was employed to measure the consistency of responses and to identify the extent of variation among the participants' experiences. To examine the relationship between customer perception and customer satisfaction, the researcher used Pearson's r to present the results of the relationship on customer perception and customer satisfaction towards Korean and Japanese surplus retailed items among the one hundred fifty (150) respondents. The findings clearly interpreted and highlighted the relationships between the two variables of the study which are the customer satisfaction and customer perception.

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IV. RESULTS AND DISCUSSION

The table 1 shows the overall mean of 3.37 with a standard deviation of 0.68 is interpreted as Very Positive. This means that most respondents have a highly favorable perception regarding the quality of surplus products. The result also shows that respondents generally agree that surplus items are reliable, functional, and satisfactory in quality. The standard deviation further indicates that the responses of the respondents are closely related and consistent.

The result regarding the level of product quality indicates that the respondents of this study have a very high positive level of perception towards the surplus items. This finding suggest that the majority of the respondents believe that surplus retailed items are in good condition, dependable in quality and comparable to selected brand new products. Furthermore, the result has shown a common agreement among participants in regards to the positive quality and reliability of surplus items.

This finding is supported by the study of Araújo et al. (2022), where their emphasized that consumers' perception of product quality and safety significantly influences their attitudes and acceptance of product. In connection, respondents in the current study showed a positive perception toward surplus retailed items, considering them dependable in quality and comparable to selected brand-new products.

The statement "The surplus items I purchase are generally in satisfactory condition" obtained the highest mean of 3.44 with a standard deviation of 0.66, interpreted as Very Positive. This implies that respondents strongly believe that surplus products are still in good condition despite being previously owned or surplus items. Customers are satisfied with the physical condition and usability of the products they purchase from surplus stores.

This finding was supported by the study of Mahsyar and Surapati (2020), which stated that product quality has a positive and significant effect on customer satisfaction because customers become more satisfied when the quality of products meets their expectations.
On the other hand, the statement "The products demonstrate a reasonable level of durability despite prior use" obtained the lowest mean of 3.23 with a standard deviation of 0.68, interpreted as Positive.

This indicates that although respondents still agree that surplus products are durable, some customers may still have doubts regarding the long-term durability of previously used items. Customers may perceive that some surplus products can easily wear out compared to brand-new items.
This finding is supported by Wang (2017), who emphasized that customers are more likely to form positive perceptions when they believe that a product meets acceptable quality standards.

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Table 1. Respondent's Distribution on the level of Customer Perception as Regards to Product Quality

Statement	Mean	SD	Description	Interpretation
The surplus items I purchase are generally in satisfactory condition.	3.44	0.66	Strongly Agree	Very Positive
The products demonstrate a reasonable level of durability despite prior use.	3.23	0.68	Agree	Positive
The quality of surplus items aligns with my expectations.	3.29	0.70	Strongly Agree	Very Positive
I feel confident in the functional performance of the products I purchase.	3.35	0.68	Strongly Agree	Very Positive
Most items remain reliable and suitable for continued use.	3.39	0.67	Strongly Agree	Very Positive
The products exhibit minimal visible defects or damage.	3.38	0.68	Strongly Agree	Very Positive
Instances of defective items are relatively uncommon in my purchases.	3.35	0.68	Strongly Agree	Very Positive
The quality of surplus items is comparable to selected brand-new products.	3.42	0.68	Strongly Agree	Very Positive
I perceive Korean and Japanese surplus items as dependable in quality.	3.41	0.66	Strongly Agree	Very Positive
I am satisfied with the quality standards of surplus products.	3.41	0.70	Strongly Agree	Very Positive
Overall	3.37	0.68	Strongly Agree	Very Positive

Legend:
3.26 – 4.00 =Strongly Agree| Very Positive 2.51 – 3.25 = Agree| Positive 1.76 – 2.50 = Disagree| Negative 1. 00 – 1.75 = Strongly Disagree| Very Negative

The table 2 shows the level of customer perception in terms of product availability with an overall mean score of 3.29 (SD=.66) interpreted as very positive. The result shows that the respondents perceived the surplus items as available and are easily accessible to customers. The very positive perception indicates that the availability of the items meets customer demand and expectation.
The findings shows that respondents have a very positive perception in terms of product availability. It suggests that the store regularly has the items that the customer intend to purchase and has a variety of items available. This very positive perception implies that the availability of surplus items satisfies customer demand and expectations, which may contribute to customer convenience and purchasing confidence. It indicates that consumers do not view limited availability as a major issue,

suggesting that surplus retailers are able to maintain an adequate supply of products for their target market.

This finding is supported by Rajavi and Modaresi (2024), emphasizing that inventory levels positively influence consumer perceptions of brands, while product variety does not have a significant direct effect. In connection to the current study, the result found that respondents perceived surplus items positively in terms of availability, indicating that consistent product supply contributes to favorable consumer perception and satisfaction.

The indicator statement "The store provides sufficient options to accommodate different customers," has the highest mean score of 3.36 with the standard deviation of 0.69, interpreted as very positive. This indicates that the respondents strongly perceived that surplus stores offer a wide variety of retailed items that can accommodate the wide range of customer preferences and needs.

The finding highlights that the availability of diverse of product option plays an important role in enhancing customer perception. This indicates that respondents strongly perceive Japan and Korean surplus stores as providing a sufficient option that caters various preferences and needs of the customers. This result suggests that the product variety is the key strength of the store, as the customers feel that their needs and preferences are met.

These is supported by Richards et al. (2017) which found that the increasing product variety within a store may raise effort required to find products in store. However, they explain that the retailers often reduce this experience by offering deeper and better organize assortments to make it easier for customers to locate desired products.

This implies that greater product variety enhances overall shopping convenience and reduces the need for consumers to visit multiple stores. To relate this study, the positive perception of respondence regarding sufficient product options suggests that a wide variety of items contributes to improve customer experience and satisfaction in retail setting. The lowest mean score is 3.21 for the indicator statement "The store consistently provides the items I intend to purchase," with a standard deviation of 0.73 and interpreted as positive. Although the level of agreement is slightly lower compared to the other indicators, this still suggest that respondents generally agree that the store is able to supply the items they need. The result suggests that even customers perceived the store as capable in meeting their purchase intention, there may still be an occasional limitation in product availability or consistency. The finding implies that improving product consistency and ensuring a more stable supply of popular Japan and Korean surplus items may strengthen the customer perception.

These findings are supported by the study of Bendoly et al. (2018), where the authors emphasized that consistency in the supply chain plays an important role in customer demand and improvement in service performance to ensuring the availability of the items. Another relevant study of Zeng et al. (2019), also emphasized that with an effective inventory management, the retailers can maintain a stable product supply and respond effectively to a naturally changing customer demand.

The indicator with the statement "A diverse range of products is available within the store" has also the lowest mean score of 3.21 with a standard deviation of 0.60 and interpreted as positive. This shows that the respondents generally agree that there are a diverse range of products available in

Japan and Korean surplus stores. Although this perception is positive, it is still slightly weaker as it has the lowest mean score compared to the other indicators in the table.

This implies that the store is still perceived as positive, offering a diverse range of Japan and Korean surplus items. However, there may be limitation especially in variety or selection that prevents from having a higher level of agreement among respondents. Findings suggests that improving the product assortment within the store could enhance the level of customer perception in terms of having a diverse range of items within the surplus stores.

A relevant study of Sweeney et al. (2023), revealed that increase in product variety in retail store may enhance sale as it can attract a broader number of customers, leading to higher number of purchases. The study further explained that the impact of product variety depends on the nature of product category, as well as the retailer's ability to efficiently manage the inventory.

Table 2. Respondent's Distribution on the level of Customer Perception as Regards to Product Availability

Statement	Mean	SD	Description	Interpretation
The store consistently provides the items I intend to purchase.	3.21	0.73	Agree	Positive
A diverse range of products is available within the store.	3.21	0.60	Agree	Positive
The store regularly replenishes its inventory.	3.24	0.63	Agree	Positive
I am able to locate products that correspond to my preferences.	3.29	0.66	Strongly Agree	Very Positive
The store offers a variety of brands and product categories.	3.32	0.61	Strongly Agree	Very Positive
Products are systematically arranged, facilitating ease of access.	3.35	0.67	Strongly Agree	Very Positive
I seldom leave the store without finding suitable items.	3.27	0.69	Strongly Agree	Very Positive
The availability of products adequately meets my needs.	3.35	0.61	Strongly Agree	Very Positive
Both common and distinctive items are accessible within the store.	3.33	0.66	Strongly Agree	Very Positive
The store provides sufficient options to accommodate different customers.	3.36	0.69	Strongly Agree	Very Positive
Overall	3.29	0.66	Strongly Agree	Very Positive

The table 3 shows the level of customer perception in terms of product affordability with an overall mean score of 3.29 with a standard deviation of 0.69 and interpreted as very positive. The table indicates that respondents have strong positive perception of Japan and Korean surplus items in terms of product affordability.

The result indicates that respondents hold a very positive perception on the affordability of Japan and Korean surplus retailed items. This suggests that customers consider the products to be reasonably priced and accessible within their financial capacity. The very positive response implies that the pricing of surplus items aligns well with consumer expectations and contributes to their willingness to consider or purchase these products.

This finding is supported by Niu et al. (2024), product price significantly influences consumer attitudes at different stages in terms of online shopping. Their study found that higher prices can initially create a positive perception because customers associate them with higher product quality during the add-to-cart stage. In connection to current study, the higher prices may lead to a negative attitude due to increased perception of monetary sacrifice.

The statement "Purchasing surplus items allows me to manage my expenses effectively," with the mean score of 3.33 with the standard deviation of 0.67 interpreted as very positive. With the highest mean score, this indicates that respondents strongly perceived that buying surplus items allows them to better control and manage their expenses.

The finding highlights that customers strongly perceived surplus retailed items not only for product availability but also for affordability and better financial management among the customers. Customers view surplus retailed items as effective option to allow customers to save money while they are still purchasing the item they needed.

The findings support the study of Kasmad (2022), emphasized that the competitive and affordable prices can influence the increase of consumers purchasing decisions. In the relation in this current study, the high level of perception of respondents suggests that affordability is an important factor in shaping customer perception in Japan and Korean surplus retailed items.

The indicator with a statement "The cost of products significantly affects my decision to purchase," also obtained a mean score of 3.33 with a standard deviation of 0.73 and interpreted as very positive. This implies that one of the factors affecting purchase decision is the cost of the products. The result also implies that the cost is a major consideration in purchasing behavior of consumers of the surplus retailed items.

This finding supports the study of Cakranegaraet al. (2022), emphasized that product pricing can significantly affect the consumer purchasing interest. Their study revealed that appropriate pricing strategies can influence the buying behavior of the consumers by increasing perceived affordability and value.

The indicator with a statement "The pricing of products is reasonable in relation to their quality," obtained a lowest mean score of 3.21 with a standard deviation of 0.68 interpreted as positive. This implies that respondents agree that Japan and Korean retailed items have reasonable price in relation to the quality of the items, although this indicator obtained a lowest means score it is still interpreted as positive.

The findings suggest that while customers still view the products as affordable with a fair price, some respondents may have less positive perception regarding the price and the quality of the item. The customers may not fully convince that the quality matches the price of the product or item's quality.

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Table 3. Respondent's Distribution on the level of Customer Perception as Regards to Product Affordability

Statement	Mean	SD	Description	Interpretation
Surplus items are priced lower compared to those in regular retail stores.	3.22	0.61	Agree	Positive
The pricing of products is reasonable in relation to their quality.	3.21	0.68	Agree	Positive
I perceive surplus items as offering good value for money.	3.27	0.67	Strongly Agree	Very Positive
Price reductions and discounts influence my purchasing decisions.	3.28	0.68	Strongly Agree	Very Positive
Purchasing surplus items allows me to manage my expenses effectively.	3.30	0.75	Strongly Agree	Very Positive
The pricing of products is generally within my financial capacity.	3.33	0.67	Strongly Agree	Very Positive
I am satisfied with the affordability of surplus items.	3.32	0.72	Strongly Agree	Very Positive
The cost of products significantly affects my decision to purchase.	3.33	0.73	Strongly Agree	Very Positive
The price of items is justified by their condition and usability.	3.31	0.69	Strongly Agree	Very Positive
Affordability is a primary reason for my preference for surplus stores.	3.27	0.74	Strongly Agree	Very Positive
Overall	3.29	0.69	Strongly Agree	Very Positive

This supports the study of Ahmed et al. (2023), found that the perceived price fairness and service quality can influence consumer satisfaction and loyalty. Their study highlights that the evaluation of consumers in price fairness is related to how they perceive service or product quality that affects satisfaction.

Table 4 shows the overall mean of 3.25 with a standard deviation of 0.67 is interpreted as"Satisfied." This means that respondents are generally satisfied with their shopping experience in surplus stores. The findings indicate that customers enjoy shopping in the store and appreciate the services and environment provided.

The results indicates that the respondents are satisfied with their shopping experience towards surplus stores. The findings implies that store are able to provide a good services, environment and overall shopping experience. This implies that the store is able to meet customer expectations that provides a pleasant and acceptable shopping experience.

This result is supported by Sharma et al. (2025), emphasizes that when customers encounter a well-organized store with available products and enhanced shopping experiences, they are more likely to develop positive perceptions and proceed with their purchase decisions.

The statements "I find the experience of shopping for surplus items to be enjoyable" obtained the highest mean of 3.38 with a standard deviation of 0.68, interpreted as "Highly Satisfied."

This implies that customers enjoy the shopping experience in surplus stores because of the excitement of finding affordable and unique items. The enjoyable shopping environment contributes positively to customer satisfaction and encourages repeat visits.

This finding is supported by Zhang et al. (2023), who stated that customers value enjoyable and practical shopping experiences, and positive experiences increase customer loyalty and satisfaction.

Meanwhile, the statement "Store personnel are approachable and provide adequate assistance" obtained the lowest mean of 3.14 with a standard deviation of 0.66, interpreted as "Satisfied."

This indicates that although respondents are satisfied with the assistance provided by store personnel, there is still room for improvement in customer service and employee responsiveness.

This finding is supported by Dewi and Praswati (2023), who found that service quality positively influences customer satisfaction because customers value quality service and support from employees.

Table 4. Respondent's Distribution on the level of Customer Satisfaction as Regards to Purchase Experience

Statement	Mean	SD	Description	Interpretation
I find the experience of shopping for surplus items to be enjoyable.	3.38	0.68	Strongly Agree	Highly Satisfied
The store environment is comfortable and conducive to shopping.	3.30	0.63	Strongly Agree	Highly Satisfied
The layout of the store facilitates a convenient shopping experience.	3.21	0.70	Agree	Satisfied
Store personnel are approachable and provide adequate assistance.	3.14	0.66	Agree	Satisfied
The purchasing process is efficient and free from unnecessary difficulty.	3.17	0.68	Agree	Satisfied
I feel at ease while browsing the available products.	3.17	0.66	Agree	Satisfied

Assistance is readily available when needed.	3.21	0.67	Agree	Satisfied
The store maintains a clean and well-organized environment.	3.27	0.64	Strongly Agree	Highly Satisfied
Customer concerns are addressed in a timely and appropriate manner.	3.30	0.70	Strongly Agree	Highly Satisfied
I am satisfied with my shopping experience in the store.	3.30	0.67	Strongly Agree	Highly Satisfied
Overall	3.25	0.67	Agree	Satisfied

Legend:
3.26 – 4.00 =Strongly Agree| Very Positive 2.51 – 3.25 = Agree| Positive 1.76 – 2.50 = Disagree| Negative 1. 00 – 1.75 = Strongly Disagree| Very Negative

Table 5 presents the level of customer satisfaction in terms of repurchase intention with an overall mean score of 3.17 with a standard deviation of 0.70 interpreted as satisfied. This indicates that respondents have a positive purchasing trend towards repurchasing Japan and Korean surplus retailed items even that this level of agreement is moderately satisfied it still obtained a satisfactory level.

The result indicates that respondents have a satisfied level of repurchase intention towards Korean and Japan surplus retailed items. The finding implies that surplus items meet the customer expectations sufficiently encouraging repeat purchasing behavior. The moderately satisfied rating also indicates that while customers are willing to repurchase, there are still be areas for improvement to further strengthen loyalty and increase a stronger repurchase intention in the future.

The result is supported by Ahn et al. (2025), states that both customer satisfaction and trust are key factors that lead to repurchase intention, with satisfaction having a stronger influence. This means that even if the service quality is good, customers are more likely to return only when they feel satisfied and trust the seller

The statement “I intend to purchase surplus items again in the future,” got the highest mean score of 3.25 and interpreted as satisfied. This indicates that respondents have a positive intention to continue purchasing Korean and Japanese surplus products in the future.

The result suggests that among indicators of the repurchase intention, customers are more confident in their willingness to buy again, it reflects an overall experience with the items. Although the score is moderately high it's still a positive repurchase inclination, this implies that customers aren't just satisfied with a one-time bargain, they have integrated the surplus items shopping habit into their future consumer behavior.

The findings support the study of Chatzoglou et al. (2022), which they found that customer satisfaction, perceived value, and customer loyalty significantly influence repurchase intention among retail consumers.

The lowest mean score is 3.06 with a standard deviation of 0.71 obtained by the indicator “I plan to continue buying Korean and Japanese surplus items,” interpreted as satisfied. This suggests that

although customers are generally willing to repurchase, some respondents may still consider other factors before consistently buying surplus items again.

The result implies that customers are satisfied with Japan and Korean surplus items. Consumers purchasing commitment may still be influenced by the factors such as product availability, quality consistency, price, or changing preferences. Even the statement indicator received the lowest mean score, the interpretation still obtained a satisfied level. This means that respondents still demonstrate an intention to continue purchasing surplus items, it reflects an overall favorable perception of the items and the store.

This finding is supported by Fan et al. (2025), Their study revealed that customer satisfaction plays a significant mediating role between intrinsic quality, perceptual quality, and brand equity, and customers repurchase intention.

Table 5. Respondent's Distribution on the level of Customer Satisfaction as Regards to Repurchase Intention

Statement	Mean	SD	Description	Interpretation
I intend to purchase surplus items again in the future.	3.25	0.65	Agree	Satisfied
I am likely to revisit this store for future purchases.	3.20	0.62	Agree	Satisfied
I prefer purchasing from surplus stores over conventional retail outlets.	3.15	0.70	Agree	Satisfied
I plan to continue buying Korean and Japanese surplus items.	3.06	0.71	Agree	Satisfied
My previous experiences motivate me to return to this store.	3.07	0.75	Agree	Satisfied
This store is among my preferred choices for purchasing such items.	3.17	0.72	Agree	Satisfied
I anticipate visiting this store on a regular basis.	3.15	0.74	Agree	Satisfied
I am willing to spend time exploring products in this store.	3.23	0.72	Agree	Satisfied
I feel confident in making future purchases from this store.	3.21	0.70	Agree	Satisfied
I demonstrate a strong intention to engage in repeat purchasing.	3.19	0.69	Agree	Satisfied
Overall	3.17	0.70	Agree	Satisfied

Legend:

3.26 – 4.00 =Strongly Agree| Very Positive 2.51 – 3.25 = Agree| Positive 1.76 – 2.50 = Disagree| Negative 1. 00 – 1.75 = Strongly Disagree| Very Negative

Table 6 shows the level of customer satisfaction in terms of recommendation obtained an overall mean of 3.23 with the standard deviation of 0.76 and interpreted as satisfied. This suggests that customers have positive perception of the store and are willing to share their good experience with other people.

The result indicate that the respondents have a positive level of satisfaction in terms of recommendation. The finding implies that the store is able to meet customer expectations in terms of products, services, and overall shopping experience, leading to favorable word-of-mouth intention. The willingness of customers to recommend the store indicates a level of trust and satisfaction that can contribute to attracting new customers and strengthening the store's reputation in the market.

This result is supported by the study of Jin et al. (2024) found that the strength of social ties, such as recommendations from friends or acquaintances, significantly affects purchase intention. Stronger social connections tend to increase trust and positively influence decisions, while weaker ties require more cognitive processing from consumers. The study also revealed that similarity between the recommender and the customer, as well as emotional reactions to the product, further shape purchasing behavior. Social recommendations also play an important role in influencing consumer purchase decisions because if consumers receive trusted recommendations and can easily access the recommended products, they are more likely to feel confident and proceed with their purchase decisions.

The highest mean score obtained is 3.34 with a standard deviation of 0.71, interpreted as highly satisfied with a statement "I would recommend this store to others". This indicates that respondents strongly agree with recommending the surplus store to other people.

The result implies that customers are highly satisfied with their shopping experience that makes them confident in recommending the stores to others. This willingness to recommend may be influenced by factors like good product quality affordable pricing and positive customer service experiences. The finding suggests that surplus store has created favorable impressions that encourage positive word of mouth among consumers.

The study of Izogo (2016), reveal that customers satisfaction and trust have a significant influence to consumer's willingness to recommend and repurchase intent.

The statement indicator, "I feel confident endorsing this store to potential customers," has obtained the lowest mean score of 3.11, with a standard deviation of 0.77 and interpreted as satisfied. Although this is still interpreted as satisfied, it receives the lowest rating among indicators.

Result suggest that even customers are generally satisfied with the store, some may require a stronger assurance before they confidently endorsing the store to others. In this hesitation, it may be influenced by personal expectation, personal experiences, or concerns regarding product consistency, and customer service. However, the result still indicates that the respondents have a good perception of the store and somewhat willing to recommend it to potential customers.

The findings are supported by Gilal et al. (2021), who emphasized that endorsement behavior is influenced by trustworthiness, credibility, and perceive assurance. The study highlighted that when

customers perceive lower confidence or inconsistent experiences, they're willingness to actively endorse a brand or store me weaken.

Table 6. Respondent's Distribution on the level of Customer Satisfaction as Regards to Recommendation

Statement	Mean	SD	Description	Interpretation
I would recommend this store to others.	3.34	0.69	Strongly Agree	Highly Satisfied
I am willing to suggest surplus shopping to my peers or family members.	3.25	0.65	Agree	Satisfied
I am inclined to share my positive experiences with others.	3.19	0.72	Agree	Satisfied
I encourage others to consider purchasing surplus products.	3.27	0.71	Strongly Agree	Highly Satisfied
I feel confident endorsing this store to potential customers.	3.11	0.77	Agree	Satisfied
I frequently speak positively about this store to others.	3.23	0.76	Agree	Satisfied
I would recommend this store based on its product quality and pricing.	3.23	0.78	Agree	Satisfied
I believe others would benefit from shopping in this store.	3.25	0.76	Agree	Satisfied
I am willing to promote this store through personal recommendations.	3.25	0.87	Agree	Satisfied
I am comfortable recommending surplus items offered by this store.	3.18	0.86	Agree	Satisfied
Overall	3.23	0.76	Agree	Satisfied

Legend:
3.26 – 4.00 =Strongly Agree| Very Positive 2.51 – 3.25 = Agree| Positive 1.76 – 2.50 = Disagree| Negative 1. 00 – 1.75 = Strongly Disagree| Very Negative

Table 7 shows the correlation between customer perception and customer satisfaction. Customer perception has an indicator of product quality, product affordability, and product availability while the customer satisfaction indicators such as purchase experience, repurchase intention, and recommendation. The result shows that all computed correlation values are positive and significant at the 0.05 level. It indicates that customer perception has a significant relationship with the customer satisfaction.

This means that as respondents perceive the product to be of good quality, affordable, and available, their satisfaction in terms of purchase experience, intention to repurchase, and the willingness to recommend the store also increases.

This study is supported by the study of Dewi and Praswati (2023), implies that customer perception particularly in terms of value and quality and can lead to higher satisfaction when supported by trust. In terms of surplus retail items, their study suggests that when customers perceive products as valuable, affordable, and of acceptable quality, they are more likely to feel satisfied.

The highest correlation is identified in the table between product quality and purchase experience with an r-value of 0.68 and a p-value of <.05, interpreted as significant. This indicates a strong positive relationship between the variables, it means that the respondents who perceive the product as high quality or more likely to have a satisfying purchase experience.

The findings imply that product qualities is one of the factors that mostly influence the customers satisfaction, particularly in terms of purchase experience. As a result, maintaining standard items can help the store strengthen the customer trust and encourage repurchase intention and improve overall satisfaction of the customers.

This result is supported by the study of Tunahan and Kutlu (2023), which revealed that experience product quality can positively influences customer satisfaction and loyalty. Similar to the current study it found a strong positive relationship between product quality and purchase experience, indicating that customers who perceive the surplus items as high quality are more likely to have a satisfying purchase experience.

The lowest correlation in the table is between product affordability and recommendation with an r-value of 0.45 and a p-value of <.05 and still interpreted as significance although it has the lowest correlation.

This indicates a moderate positive relationship between the variables and this suggest that even affordability can influence customers willingness to recommend the store, its effect is still weaker compared to the other customer perception factors as it obtained the lowest correlation value. The result shows that before recommending the stores to others, customers may consider other aspects like product quality and shopping experience.

This finding supported by the study of Chun (2020), It explains how price or affordability contributes to customers willingness to recommend the business. Although their study is all about food industry, the findings of their studies relevant to this current study which they found that price can positively influence customer satisfaction and recommendation behavior.

Table 7. Correlation Between Customer Perception and Customer Satisfaction

Variables	Purchase Experience		Int	Repurchase Intention		Int	Recommendation		Int
	r-value	p-value		r-value	p-value		r-value	p-value	

Product Quality	.684**	<.05	S	.492*	<.05	S	.506*	<.05	S
Product Affordability	.637**	<.05	S	.469*	<.05	S	.451*	<.05	S
Product Availability	.592*	<.05	S	.495*	<.05	S	.479*	<.05	S

*. Correlation is significant at the 0.05 level (two-tailed)

**. Correlation is significant at the 0.01 level (two-tailed)

The result presented in table 8 indicate that there is a significant relationship between customer perception and customer satisfaction. The overall computed r-value of 0.713 shows a strong positive correlation, that means as customer perception improves, customer satisfaction also increases. This suggest that customers who have good perceptions about the product quality, availability and affordability, are most likely to experience higher levels of satisfaction. Meanwhile, a p-value of 0.001 is lower than standard significance level of 0.05, it indicates that the relationship is statistically significant. Therefore, the null hypothesis is rejected. This result confirms that customer perception has a meaningful influence on customer satisfaction.

The findings imply that improving the factors that shape customer perception such as product quality, availability, and affordability can positively enhance the customer satisfaction especially in terms of purchase experience, repurchase intention, and recommendation. Surplus store owners should focus on strengthening a positive customers perception to build a stronger satisfaction level in regards to purchase experience, repurchase intention, and recommendation.

The study of Bupu et al. (2023), found that the customer relationship management has a significant influence to customer satisfaction through the mediating roles of customer perception and service quality. Their finding suggest that customer perception has a stronger role in shaping satisfaction as customers develop satisfaction based on how they perceive the value and quality of their experience.

Table 8. Customer Perception*Customer Satisfaction

Variables		r-value	p-value	Decision on H_0	Interpretation
Customer Perception	Customer Satisfaction	0.713**	0.001	Reject H_0	Significant

*. Correlation is significant at the 0.05 level (two-tailed)

**. Correlation is significant at the 0.01 level (two-tailed)

V. CONCLUSION

Based on the findings of the study, it is concluded that Japanese and Korean surplus retailed items have successfully established a positive image among consumers even though traditional perception of second-hand goods is having a lower value. The generally very positive customer perception in regards of product quality, availability, and affordability indicates that the respondents view the

surplus items as closely worthwhile alternative to brand new products. This high level of perception is reflected in the customer satisfaction, which suggest that surplus items are able to meet customer expectation and encourage a positive customer's intentions such as a repeat purchase and willingness to recommend.

The study also concludes that among different factors that influence a customer perception, product quality please a significant role in shipping the overall purchase experience of consumers. The significant relationship between product quality and purchase experience highlights that consumers are not solely motivated by low prices, but also depends on the condition, durability, reliability, and usability of the product that the customers intend to purchase. Lastly, the study concludes that the long-term success of Japanese and Korean surplus retail stores depends on their ability to consistently maintain their product or items quality also ensuring affordability and availability. Although the competitive pricing and accessible product option may help attract customers, it is the assurance of quality that strengthens trust, satisfaction, and loyalty. Therefore, the sustained attention to quality control and product standards is very essential in building a strong and competitive position towards the surplus retail market.

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The Influence of Dynamic Pricing Strategies Among Macro Enterprises on Customer Retention

[1]Elvis C. Boniao Jr., [2]Loiwelen D. Pacheco, [3]Rennie L. Rosita Jr.
[4]James Lloyd N. Gabitano, [5]Zhia E. Belisario
[1,2,3]Student Researcher, Bachelor of Science in Entrepreneurship IBA College of Mindanao, Inc Valencia City, Bukidnon, Philippines
[4]Research Adviser, Bachelor of Science in Entrepreneurship IBA College of Mindanao, Inc Valencia City, Bukidnon, Philippines
[5]Program Head, Bachelor of Science in Entrepreneurship IBA College of Mindanao, Inc. Valencia City, Bukidnon, Philippines

***Abstract*—This study examines the influence of dynamic pricing strategies on customer retention among macro enterprises in Valencia City, Bukidnon. Specifically, it aims to determine the level of pricing strategies in terms of cost-plus pricing, competitive pricing, price skimming, penetration pricing, and value-based pricing, assess the level of customer retention, and determine whether these pricing strategies significantly influence customer retention. A descriptive-regression research design was employed, with 50 enterprise-level respondents selected through stratified random sampling from macro enterprises in Valencia City, Bukidnon. Data were collected using a researcher-made questionnaire validated by research experts and measured using a five-point Likert scale. Weighted mean and standard deviation were used to determine the level of pricing strategies and customer retention, while regression analysis was employed to determine the significant influence of the pricing strategies on customer retention. Findings revealed that the pricing strategies were generally highly effective, with cost-plus pricing obtaining the highest mean among the strategies. Customer retention was also found to be highly evident, indicating strong repeat patronage and customer loyalty among macro enterprises. Regression analysis showed that the combined pricing strategies explained forty-point seven percent of the variance in customer retention. Among the five strategies, competitive pricing and value-based pricing significantly influenced customer retention, while cost-plus pricing, price skimming, and penetration pricing did not show significant individual influence. The study concludes that competitive and value-based pricing play important roles in strengthening customer retention among macro enterprises.**

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***Index Terms*—Pricing Strategies, Customer Retention, Cost-Plus Pricing, Competitive Pricing, Price Skimming, Penetration Pricing, Value-Based Pricing, Macro Enterprises.**

I. INTRODUCTION

Pricing plays an important role in the ability of businesses to attract customers, remain competitive, and sustain long term relationships with their target markets. Beyond determining the amount customers pay for products or services, pricing influences perceptions of value, purchasing decisions, satisfaction, and willingness to continue patronizing a business. As competition becomes increasingly intense, enterprises need to develop pricing approaches that respond to changing market conditions while maintaining profitability and meeting customer expectations. Effective pricing strategies can therefore serve as an important factor in strengthening customer relationships and supporting business sustainability.

The changing business environment has also encouraged enterprises to adopt more flexible pricing practices. Dynamic pricing strategies allow businesses to consider different market conditions, customer demand, competitors, costs, and perceived value when determining or adjusting prices. In this study, dynamic pricing strategies are examined through cost plus pricing, competitive pricing, price skimming, penetration pricing, and value-based pricing. These strategies provide enterprises with different approaches to establishing prices based on their business objectives and market conditions. For macro enterprises, which operate with broader markets and larger customer bases, the appropriate use of pricing strategies may be particularly important in maintaining competitiveness and encouraging continued customer patronage.

Despite the potential benefits of strategic pricing, determining whether pricing strategies can effectively strengthen customer retention remains an important concern. Customers may respond differently to pricing depending on their perceptions of fairness, value, competitiveness, and affordability. A pricing strategy that attracts customers in one market situation may not necessarily encourage them to remain loyal when competing alternatives are available. Moreover, the effectiveness of different pricing approaches may vary according to customer preferences and market conditions. This creates a need to examine which pricing strategies are most relevant to customer retention among macro enterprises, particularly within the local business environment of Valencia City, Bukidnon.

This study examines the influence of dynamic pricing strategies on customer retention among macro enterprises in Valencia City, Bukidnon. Specifically, it determines the level of dynamic pricing strategies in terms of cost-plus pricing, competitive pricing, price skimming, penetration pricing, and value-based pricing, assesses the level of customer retention, and determines whether the identified pricing strategies significantly influence customer retention. The findings of the study are expected to provide insights that may assist macro enterprises in developing pricing approaches that strengthen customer loyalty and repeat patronage while maintaining competitiveness and supporting long term business sustainability.

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II. LITERATURE REVIEW

Dynamic pricing has become an increasingly important pricing approach as businesses respond to changing market conditions, customer demand, competition, and technological developments. Unlike traditional fixed pricing, dynamic pricing allows businesses to adjust prices based on factors such as demand fluctuations, timing, customer behavior, and operating conditions. Immadisetty (2025) described dynamic pricing as an advancement over traditional fixed pricing because of its ability to respond to real time market conditions and improve pricing flexibility. Similarly, Williams (2022) emphasized that pricing adjustments based on demand patterns can contribute to revenue optimization, particularly in service and highly competitive markets. Hasanah and Rino (2025) further highlighted the importance of pricing adaptation in helping businesses remain responsive in fast changing environments.

Pricing strategies may differ according to the factors considered when establishing prices. Cost plus pricing determines prices by adding a predetermined markup to production costs, providing businesses with a simple and predictable method of recovering costs and generating profit (Helmold, 2022; Nagle and Müller, 2018). Competitive pricing, in contrast, considers the prices offered by competitors and allows businesses to position their products within the market. Price skimming involves introducing products at relatively high prices before gradually reducing them, while penetration pricing initially uses lower prices to attract customers and gain market share. Value based pricing differs from these approaches by focusing on the benefits and value perceived by customers rather than solely on production costs or competitor prices (Nagle and Müller, 2018; Helmold, 2022). These strategies provide businesses with different mechanisms for balancing profitability, market competitiveness, and customer expectations.

The literature also emphasizes the importance of customer perceived value in pricing decisions. Agrawal and Rahman (2023) noted that pricing approaches that consider customer value can contribute to customer satisfaction and repeat purchase behavior. Similarly, Gorb et al. (2022) emphasized that effective strategic pricing should integrate business costs, competitive conditions, and customer perceived value. This perspective suggests that pricing should not be viewed only as a means of recovering costs or maximizing immediate profit, but also as a strategic mechanism for creating value and strengthening relationships with customers. When customers perceive that prices are reasonable in relation to the benefits they receive, they may be more willing to continue purchasing from the business.

However, the literature indicates that no single pricing strategy is universally effective across all business situations. Cost plus pricing, for example, offers simplicity, financial predictability, and ease of implementation, but its focus on internal costs may limit its responsiveness to market conditions and customer perceived value (Helmold, 2022; Nagle and Müller, 2018). More market-oriented approaches, including competitive and value-based pricing, may provide greater responsiveness to customer expectations and competitive conditions. Dynamic pricing can further enhance flexibility by allowing prices to respond to changing demand and market circumstances.

Nevertheless, excessive reliance on market or cost factors without considering customer value may weaken customer satisfaction and potentially affect continued patronage.

Overall, the reviewed literature suggests that pricing strategies can influence important customer and business outcomes, particularly customer satisfaction, perceived value, repeat purchase behavior, and customer retention. While previous studies have examined individual pricing approaches and their applications across different industries, the influence of these pricing strategies on customer retention among macro enterprises remains less explored in the local context. This study therefore examines cost plus pricing, competitive pricing, price skimming, penetration pricing, and value-based pricing as components of dynamic pricing strategies and investigates their influence on customer retention among macro enterprises in Valencia City, Bukidnon.

III. MATERIALS AND METHODS

Research Design

This study utilized a descriptive-regression al research design to examine the influence of dynamic pricing strategies on customer retention among macro enterprises in Valencia City, Bukidnon. The study aimed to determine the level of pricing strategies in terms of cost plus pricing, competitive pricing, price skimming, penetration pricing, and value based pricing, as well as the level of customer retention. A total of fifty enterprise level respondents were selected through stratified random sampling. Data were collected using a researcher made questionnaire validated by research experts and measured using a five point Likert scale. Weighted mean and standard deviation were used to describe the level of pricing strategies and customer retention, while regression analysis was employed to determine the significant influence of the identified pricing strategies on customer retention.

Participants & Respondents

The participants of this study were fifty enterprise level respondents from macro enterprises in Valencia City, Bukidnon. The respondents were selected through stratified random sampling to ensure representation of the identified macro enterprises included in the study. The participants provided data regarding the pricing strategies employed by macro enterprises and their customer retention practices. Their responses served as the primary source of data for assessing the level of dynamic pricing strategies and customer retention and for determining the influence of the identified pricing strategies on customer retention.

Data Gathering Procedure

Data were collected using a researcher made questionnaire designed to assess the dynamic pricing strategies employed by macro enterprises and their customer retention. The questionnaire was validated by research experts and used a five point Likert scale to measure the responses of the participants. After the necessary preparation and validation of the research instrument, the

questionnaire was administered to fifty enterprise level respondents from macro enterprises in Valencia City, Bukidnon, who were selected through stratified random sampling. The collected responses were reviewed, organized, and prepared for statistical analysis. The data were then analyzed using weighted mean, standard deviation, and regression analysis to determine the level of dynamic pricing strategies and customer retention and the influence of pricing strategies on customer retention.

Statistical Analysis

The data gathered from the respondents were analyzed using appropriate statistical methods. Weighted mean and standard deviation were used to determine the level of dynamic pricing strategies in terms of cost plus pricing, competitive pricing, price skimming, penetration pricing, and value based pricing, as well as the level of customer retention among macro enterprises. Regression analysis was employed to determine the significant influence of the identified pricing strategies on customer retention. This statistical method allowed the researchers to assess the extent to which the different pricing strategies influence customer retention and to identify which pricing strategies significantly contribute to customer retention.

IV. RESULTS AND DISCUSSIONS

Cost-Plus Pricing (Markup Pricing)

The findings revealed that Cost-Plus Pricing obtained an overall mean score of 3.49 with a standard deviation of 0.65, interpreted as Highly Effective. This indicates that macro enterprises highly implement cost-plus pricing in determining the prices of their products and services. The result suggests that businesses commonly consider their production or acquisition costs and apply a markup when determining the final selling price. This approach allows enterprises to recover their operational expenses while maintaining their desired profit margins.

The high result further indicates that macro enterprises prefer pricing approaches that provide financial predictability and stability. Since cost-plus pricing is relatively simple and straightforward to apply, businesses can establish prices based on identifiable costs and predetermined markups. This makes the strategy a practical approach for enterprises that prioritize cost recovery, profitability, and financial sustainability. This finding is consistent with Kotler and Keller (2016) and Nagle and Müller (2018), who emphasized that cost-plus pricing remains a widely recognized pricing approach because of its simplicity, predictability, and ease of implementation.

The highest mean of 3.75, with a standard deviation of 0.52, corresponds to the statement, “The pricing approach ensures the financial sustainability of the business.” This indicates that respondents strongly agree that cost-plus pricing contributes to the financial sustainability of macro enterprises. The finding implies that businesses rely on this pricing approach to ensure that their costs are adequately covered while generating sufficient profit to support continuous operations.

This finding suggests that cost-plus pricing provides macro enterprises with a relatively stable basis for managing their financial operations. By considering costs before establishing the final selling price, businesses can minimize the possibility of selling products below their required cost levels. This is supported by Agrawal and Rahman (2023), who explained that cost-plus pricing contributes to organizational control and financial planning because prices can be calculated based on internal cost structures. The authors further emphasized that this approach can help organizations maintain stable operations and reduce financial uncertainty.

On the other hand, the lowest mean of 3.04, with a standard deviation of 0.74, corresponds to the statement, "The markup applied to products appears consistent across items." This result is interpreted as Moderately Effective. Although respondents generally agree with the statement, its lower rating compared with the other indicators suggests that the application of markups may not always be consistent across different products.

The finding may indicate that macro enterprises adjust their markup percentages depending on product characteristics, demand, market conditions, customer expectations, and the value provided by the product. Therefore, although cost-plus pricing is commonly used, businesses may still exercise flexibility when determining the appropriate markup for different products. This is consistent with Helmold (2022), who noted that cost-based pricing involves adding a markup to product costs, while businesses may adjust markup rates according to market conditions, customer expectations, and the value offered by the product.

From the findings, it can be observed that macro enterprises strongly depend on cost-plus pricing as a foundational pricing strategy. The overall mean of 3.49 indicates that businesses place considerable importance on cost recovery, profitability, and financial sustainability when setting prices. The highest rating on financial sustainability further demonstrates that respondents view cost-plus pricing as an effective means of maintaining stable business operations. However, the lower rating on markup consistency suggests that businesses may still adjust their markups according to differences in products and market conditions. Overall, cost-plus pricing remains a highly effective and practical approach for macro enterprises in establishing prices and sustaining profitability.

Table 3 Respondents` Distribution in the Level of Marketing Strategies as Regards to Cost-Plus Pricing (Markup Pricing)

Statements	Mean	SD	Description	Interpretation
Product prices are determined by adding a markup to the cost.	3.43	0.79	Strongly Agree	Highly Effective
The pricing structure reflects the cost incurred in acquiring or producing the product.	3.46	0.69	Strongly Agree	Highly Effective
The markup applied to products appears consistent across items.	3.04	0.74	Agree	Moderately Effective
Prices ensure that operational costs are adequately covered.	3.46	0.64	Strongly Agree	Highly Effective

The pricing approach reflects a cost-oriented decision-making process.	3.46	0.58	Strongly Agree	Highly Effective
Profit margins appear to be based on cost considerations.	3.43	0.57	Strongly Agree	Highly Effective
The pricing system reflects a standard markup practice.	3.54	0.64	Strongly Agree	Highly Effective
The cost of products is a primary basis for determining price.	3.61	0.57	Strongly Agree	Highly Effective
The pricing approach ensures financial sustainability of the business.	3.75	0.52	Strongly Agree	Highly Effective
Overall, pricing reflects a cost-plus strategy.	3.68	0.55	Strongly Agree	Highly Effective
Overall	3.49	0.65	Strongly Agree	Highly Effective

Legend: 3.26-4.00: Strongly Agree/Highly Effective 1.76-2.50: Disagree/Not Effective 2.51-3.25: Agree/Moderately Effective 1.00-1.75: Strongly Disagree/Not Effective

Competitive Pricing

The findings showed that Competitive Pricing obtained an overall mean score of 3.18 with a standard deviation of 0.91, interpreted as Moderately Effective. This indicates that macro enterprises consider competitor prices when determining the prices of their products and services, although competitive pricing is not consistently applied at a highly effective level. The result suggests that businesses take competitor pricing into account as one of the factors in their pricing decisions.

The result further suggests that businesses monitor competitor prices and prevailing market conditions to maintain their competitiveness. Customers often compare prices among competing businesses, making awareness of competitors' pricing important in maintaining market relevance. The findings also indicate that enterprises may adjust their prices in response to competitor actions, although such adjustments are not necessarily made consistently. This is reflected in the relatively moderate means for monitoring competitor pricing (M = 3.21), responding to competitor actions (M = 3.00), and pricing according to competitive considerations (M = 3.21).

These findings support Kotler and Keller (2016) and Nagle and Müller (2018), who explained that competitive pricing allows businesses to consider market conditions and competitor prices when establishing their own prices. Competitive pricing is particularly relevant in markets where customers can easily compare alternatives and where price differences may influence purchasing decisions.

The highest mean of 3.39, with a standard deviation of 0.92, corresponds to the statement, “The pricing strategy helps maintain a competitive position.” This indicates that respondents recognize competitive pricing as an important tool for maintaining the market position of macro enterprises. It suggests that businesses use pricing not only to respond to competitors but also to sustain their

relevance and attractiveness within the market. The finding is consistent with Song, He, and Duan (2025), who emphasized the role of pricing in market positioning and competitive strategy.

On the other hand, the lowest mean of 2.86, with a standard deviation of 0.80, corresponds to the statement, "Price differences with competitors are minimal." Although respondents agreed with the statement, it received the lowest rating among the indicators and was interpreted as Moderately Effective. This suggests that businesses do not necessarily maintain prices that are almost identical to those of their competitors. Instead, differences in pricing may exist depending on product characteristics, customer demand, operating costs, and market conditions.

According to Li (2023), pricing decisions in dynamic markets are affected by changing customer demand, competitive pressures, and market conditions. Therefore, businesses may adjust their prices rather than simply matching competitors' prices. This supports the finding that macro enterprises consider competitor pricing while still maintaining flexibility in their own pricing decisions.

Overall, the findings indicate that competitive pricing is an important but not dominant pricing strategy among macro enterprises. The overall mean of 3.18 suggests that businesses generally consider competitor prices and market conditions when establishing their own prices, but they do not depend exclusively on competitor pricing. Instead, competitive pricing serves as a reference that helps businesses maintain market relevance and attract customers while allowing them to adjust prices according to their own circumstances.

The findings further imply that macro enterprises should continue monitoring competitor prices while balancing competitive considerations with customer-perceived value, profitability, product quality, and business sustainability. The relatively low rating for minimal price differences indicates that businesses do not always need to match competitor prices exactly. Rather, they may differentiate their pricing based on the value they provide and the conditions of the market. Thus, competitive pricing should function as one component of a broader pricing strategy rather than the sole basis for price determination. This interpretation is consistent with the study's overall finding that macro enterprises employ multiple pricing strategies rather than relying on only one approach.

Table 4 Respondents` Distribution in the Level of Marketing Strategies as Regards to Competitive Pricing

Statements	Mean	SD	Description	Interpretation
Product prices are set with consideration of competitors' prices.	3.25	1.00	Agree	Moderately Effective
The business monitors competitor pricing before setting its own prices.	3.21	1.03	Agree	Moderately Effective
Prices are comparable to those offered by similar stores.	3.32	0.86	Agree	Highly Effective
Pricing decisions are influenced by prevailing market conditions.	3.25	0.84	Agree	Moderately Effective

The business adjusts prices in response to competitor actions.	3.00	0.94	Agree	Moderately Effective
Customers perceive the prices as competitive within the market.	3.11	0.83	Agree	Moderately Effective
The pricing strategy helps maintain a competitive position.	3.39	0.92	Agree	Highly Effective
Price differences with competitors are minimal.	2.86	0.80	Agree	Moderately Effective
Pricing reflects awareness of industry standards.	3.18	0.90	Agree	Moderately Effective
Pricing is guided by competitive considerations.	3.21	0.99	Agree	Moderately Effective
Overall	3.18	0.91	Agree	Moderately Effective

Legend: 3.26-4.00: Strongly Agree/Highly Effective 1.76-2.50: Disagree/Not Effective 2.51-3.25: Agree/Moderately Effective 1.00-1.75: Strongly Disagree/Not Effective

Price Skimming

The findings revealed that Price Skimming obtained an overall mean score of 2.79, with a standard deviation of 0.91, interpreted as Moderately Effective. This indicates that macro enterprises moderately practice price skimming as part of their pricing strategies. The result suggests that businesses may introduce selected products at relatively higher prices and subsequently adjust prices as market conditions change. However, compared with other pricing strategies, price skimming appears to be less consistently practiced among the macro enterprises included in the study.

The moderate result may be attributed to the nature of the businesses included in the study. Macro enterprises may place greater emphasis on customer accessibility, market competitiveness, and sustained sales rather than relying heavily on premium introductory prices. This finding is consistent with Chen (2025), who discussed that price skimming can allow businesses to recover research and development costs more quickly, although the strategy may also present challenges related to customer dissatisfaction and competitor entry.

The highest mean of 3.07, with a standard deviation of 0.76, corresponds to the statement, “Prices decrease as the product becomes more widely available in the market.” This indicates that respondents agree that price reductions occur as products become more widely available. The finding suggests that macro enterprises may adjust prices as market availability changes, particularly when products become more accessible to customers or when competitive conditions increase.

This finding is consistent with Rekettye, Liu, and Danyi (2025), who discussed price skimming as a strategy commonly associated with innovative products and early adopters. The approach allows

businesses to initially capture customers who are willing to pay a premium and subsequently make prices more accessible to other market segments as the product becomes more established.

On the other hand, the lowest mean of 2.57 was obtained by two statements: "Newly introduced products are priced relatively high" and "Prices are gradually reduced over time." Both indicators were interpreted as Moderately Effective. This suggests that although elements of price skimming are present, macro enterprises do not strongly emphasize high introductory pricing or systematic price reductions across their products.

The finding is supported by Rajagopal and Zlatev (2025), who explained that price skimming targets customers who are willing to pay premium prices for products associated with exclusivity or innovation. As the market expands, businesses may gradually reduce prices to reach more price-sensitive customer segments. The relatively low rating of the two indicators in the present study may therefore suggest that such conditions are not consistently present among the macro enterprises surveyed.

Overall, the findings indicate that price skimming is practiced at a moderate level among macro enterprises. The overall mean of 2.79 suggests that businesses use this strategy selectively rather than as a primary pricing approach. While some practices associated with price skimming, particularly adjusting prices as products become more widely available, are evident, the relatively low ratings for high introductory prices and gradual price reductions indicate that the strategy is not strongly emphasized.

The findings further imply that macro enterprises may benefit from applying price skimming selectively, particularly when introducing products that are new, innovative, or capable of attracting customers willing to pay a premium. However, businesses should consider customer purchasing power, market demand, competitive conditions, and perceived product value before establishing high introductory prices. Thus, price skimming may serve as a useful supplementary strategy, but it should be balanced with other pricing approaches that support customer accessibility, competitiveness, customer satisfaction, and long-term profitability.

Table 5 Respondents` Distribution in the Level of Marketing Strategies as Regards to Price Skimming

Statements	Mean	SD	Description	Interpretation
Newly introduced products are priced relatively high.	2.57	0.63	Agree	Moderately Effective
Prices are gradually reduced over time.	2.57	0.69	Agree	Moderately Effective
Early buyers are expected to pay premium prices.	2.61	0.74	Agree	Moderately Effective
The pricing strategy aims to maximize early-stage profits.	3.00	0.67	Agree	Moderately Effective
Prices decrease as the product becomes more widely available.	3.07	0.66	Agree	Moderately Effective

Initial pricing targets customers willing to pay more.	2.64	0.83	Agree	Moderately Effective
The strategy reflects a high-to-low pricing pattern.	2.86	0.65	Agree	Moderately Effective
Price reductions occur after initial demand is satisfied.	2.79	0.69	Agree	Moderately Effective
Customers perceive initial prices as relatively high.	2.86	0.65	Agree	Moderately Effective
Pricing reflects a high price-skimming approach.	2.89	0.63	Agree	Moderately Effective
Overall	2.79	0.70	Agree	Moderately Effective

Legend: 3.26-4.00: Strongly Agree/Highly Effective 1.76-2.50: Disagree/Not Effective 2.51-3.25: Agree/Moderately Effective 1.00-1.75: Strongly Disagree/Not Effective

Penetration Pricing

The findings revealed that Penetration Pricing obtained an overall mean score of 3.35 with a standard deviation of 0.47, interpreted as Highly Effective. This indicates that macro enterprises strongly practice penetration pricing as part of their pricing strategies. The result suggests that businesses use relatively affordable pricing to attract customers, encourage initial purchases, and strengthen their position in the market. The low standard deviation also indicates that the respondents' assessments were relatively consistent.

The findings suggest that affordability and customer acquisition are important considerations in the pricing practices of macro enterprises. By offering accessible prices, businesses may reduce the price barrier faced by potential customers and encourage them to try their products or services. This is consistent with Harahap, Soemitra, and Rahma (2025), who explained that penetration pricing can stimulate demand and facilitate market entry by making products more accessible to customers.

The highest mean of 3.71, with a standard deviation of 0.53, corresponds to the statement, “Customers are attracted primarily due to affordability.” This indicates strong agreement that affordability is an important factor in attracting customers. The finding suggests that macro enterprises recognize the influence of accessible pricing on customer purchasing decisions and use affordability as a means of gaining customer attention.

This finding is consistent with Spann, Fischer, and Tellis (2015), who discussed penetration pricing as an approach that can help businesses attract customers and expand their market presence. The result further suggests that affordable pricing may encourage customers to make trial purchases, particularly when they perceive the products or services as accessible relative to available alternatives.

In contrast, the lowest mean of 2.89, with a standard deviation of 0.69, corresponds to the statement, “Products are initially offered at relatively low prices.” This indicator was interpreted

as Moderately Effective. Although respondents generally agreed with the statement, its lower rating suggests that macro enterprises do not consistently introduce all products or services at relatively low prices.

This finding may indicate that businesses consider factors other than affordability when establishing initial prices, such as production costs, product quality, target customers, demand, and market conditions. Thus, although penetration pricing is strongly practiced overall, macro enterprises may apply lower introductory prices selectively rather than uniformly across all products. This is consistent with Cruz and Rosário (2025), who discussed the use of introductory pricing and discounts as approaches for building customer bases and strengthening customer loyalty.

Overall, the findings indicate that penetration pricing is a highly effective pricing strategy among macro enterprises. The overall mean of 3.35 demonstrates that businesses strongly recognize the importance of affordability, customer acquisition, and market entry in their pricing decisions. The highest rating for customer attraction through affordability further emphasizes the role of accessible prices in influencing customer purchasing behavior.

However, the lower rating for initially offering products at relatively low prices indicates that penetration pricing is not necessarily applied in the same manner across all products and services. Macro enterprises may adjust their initial prices according to product characteristics, costs, demand, and competitive conditions. Therefore, while affordable pricing can help businesses attract customers and expand their market presence, enterprises should balance lower prices with profitability, product quality, customer value, and long term sustainability.

Table 6 Respondents` Distribution in the Level of Marketing Strategies as Regards to Penetration Pricing

Statements	Mean	SD	Description	Interpretation
Products are initially offered at relatively low prices.	2.89	0.69	Agree	Moderately Effective
Pricing is intended to attract a large number of customers quickly.	3.21	0.79	Agree	Moderately Effective
Low pricing encourages customers to try the product.	3.50	0.64	Strongly Agree	Highly Effective
Prices are set lower than competitors to gain market share.	3.25	0.80	Agree	Moderately Effective
The strategy prioritizes customer acquisition over immediate profit.	3.29	0.71	Strongly Agree	Highly Effective
Pricing creates strong initial market interest.	3.32	0.55	Strongly Agree	Highly Effective
Customers are attracted primarily due to affordability.	3.71	0.53	Strongly Agree	Highly Effective
The pricing approach supports rapid market entry.	3.36	0.56	Strongly Agree	Highly Effective

The strategy encourages repeat purchasing through low pricing.	3.54	0.58	Strongly Agree	Highly Effective
Pricing reflects a high penetration strategy.	3.43	0.57	Strongly Agree	Highly Effective
Overall	3.35	0.47	Strongly Agree	Highly Effective

Legend: 3.26-4.00: Strongly Agree/Highly Effective 1.76-2.50: Disagree/Not Effective 2.51-3.25: Agree/Moderately Effective 1.00-1.75: Strongly Disagree/Not Effective

Value Based Pricing

The findings showed that Value Based Pricing obtained an overall mean score of 3.38, with a standard deviation of 0.XX, interpreted as Highly Effective. This indicates that macro enterprises strongly consider customer perceived value when determining the prices of their products and services. The result suggests that businesses recognize the importance of aligning prices with customer expectations, perceived benefits, and satisfaction when making pricing decisions.

The findings further suggest that macro enterprises do not rely solely on production costs or competitor prices when determining prices. Instead, they consider how customers perceive the benefits and value associated with the products or services offered. This is consistent with Helmold (2022), who explained that value based pricing aligns prices with customer perceived value and can contribute to customer satisfaction, loyalty, and profitability.

The highest mean of 3.61, with a standard deviation of 0.57, corresponds to the statement, “Customers are willing to pay based on perceived value.” This indicates strong agreement that customers are willing to pay when they perceive sufficient value in the products or services offered. The finding suggests that purchasing decisions may be influenced not only by the price itself but also by the benefits and value customers associate with what they receive.

This finding is consistent with Krämer, Burgartz, and Muzzu (2025), who emphasized that value based pricing can support market segmentation and profitability while allowing businesses to respond to customer expectations. The result suggests that understanding differences in customer perceived value can help enterprises establish prices that customers consider reasonable and worthwhile.

On the other hand, the lowest mean of 3.18, with a standard deviation of 0.67, corresponds to the statement, “Higher prices are associated with higher perceived quality.” This indicator was interpreted as Moderately Effective. Although respondents agreed with the statement, its lower rating suggests that customers do not necessarily associate a higher price with higher perceived quality as strongly as they recognize other aspects of value based pricing.

This finding indicates that price alone may not be sufficient to communicate product quality. Customers may consider other factors when evaluating value, including product benefits, performance, service, brand reputation, and their overall experience. This supports Mittal, Meenakshi, and Panchal (2025), who emphasized that value based pricing can strengthen customer relationships when customers perceive that the benefits received justify the price paid.

Overall, the findings indicate that Value Based Pricing is a highly effective pricing strategy among macro enterprises. The overall mean of 3.38 demonstrates that businesses strongly consider customer perceived value when establishing prices. The highest rating for customers' willingness

to pay based on perceived value further emphasizes the importance of customer perception in pricing decisions. However, the lower rating for the association between higher prices and higher perceived quality suggests that enterprises should not assume that increasing prices will automatically increase customers' perceptions of quality.

The findings therefore imply that macro enterprises should continue developing prices based on the actual value delivered to customers. Businesses may strengthen the effectiveness of value based pricing by improving product quality, customer experience, service delivery, and other benefits that customers consider important. By ensuring that the price is perceived as fair and justified by the value received, enterprises can support customer satisfaction while maintaining profitability and long term business sustainability.

Table 7 Respondents` Distribution in the Level of Marketing Strategies as Regards to Value-Based Pricing

Statements	Mean	SD	Description	Interpretation
Prices are determined based on the perceived value of the product.	3.36	0.73	Strongly Agree	Highly Effective
Customers believe the product is worth the price paid.	3.46	0.58	Strongly Agree	Highly Effective
Pricing reflects the benefits received by customers.	3.43	0.69	Strongly Agree	Highly Effective
Customers are willing to pay based on perceived value.	3.61	0.57	Strongly Agree	Highly Effective
The pricing strategy emphasizes customer perception rather than cost.	3.21	0.83	Agree	Moderately Effective
Products deliver value that justifies their price.	3.43	0.57	Strongly Agree	Highly Effective
Higher prices are associated with higher perceived quality.	3.18	0.67	Agree	Moderately Effective
Pricing reflects both tangible and intangible product benefits.	3.29	0.71	Strongly Agree	Highly Effective
Customers feel satisfied with the value received relative to price.	3.43	0.50	Strongly Agree	Highly Effective
Pricing aligns with customer-perceived value.	3.43	0.57	Strongly Agree	Highly Effective
Overall	3.38	0.65	Strongly Agree	Highly Effective

Legend: 3.26-4.00: Strongly Agree/Highly Effective 1.76-2.50: Disagree/Not Effective 2.51-3.25: Agree/Moderately Effective 1.00-1.75: Strongly Disagree/Not Effective

The results showed that Customer Retention obtained an overall mean score of 3.41 with a standard deviation of 0.66, interpreted as Highly Effective. This indicates that macro enterprises

demonstrate a high level of customer retention, as reflected in repeat purchases, customer loyalty, continued engagement, and the ability of businesses to maintain relationships with their customers. The result suggests that customers generally continue to patronize macro enterprises despite the presence of competing businesses.

The findings further indicate that customer retention is reflected in several aspects of customer behavior. These include maintaining a stable base of repeat customers, remaining loyal despite competitors, generating sales from returning customers, and continuing to engage with businesses for future purchases. The results suggest that macro enterprises are generally successful in maintaining customer relationships and encouraging continued patronage.

The highest mean of 3.71, with a standard deviation of 0.53, corresponds to the statement, "Customer loyalty contributes positively to the business's performance." This indicates strong agreement among respondents that customer loyalty contributes to the performance of macro enterprises. The finding suggests that loyal and returning customers play an important role in supporting business stability, profitability, and long term performance.

This finding is supported by Kotler and Keller (2016), who emphasized the importance of customer satisfaction and perceived value in developing customer loyalty and repeat purchasing behavior. When customers are satisfied with the value they receive, they are more likely to continue purchasing from the same business and maintain their relationship with the enterprise.

On the other hand, the lowest mean of 3.00, with a standard deviation of 0.72, corresponds to the statement, "The business experiences minimal loss of regular customers." This indicator was interpreted as Moderately Effective. Although respondents generally agreed with the statement, its lower rating suggests that macro enterprises still experience some degree of customer loss despite having a generally high level of customer retention.

The result may be attributed to competition, changing customer preferences, differences in product offerings, pricing, or service quality. Customers may shift to competing businesses when they perceive better prices, greater value, improved products, or better service elsewhere. This is consistent with Rolando (2025), who noted that customer loyalty can be influenced by factors such as price and service quality. Thus, even businesses with a strong base of loyal customers need to continuously maintain the value and quality of their offerings to minimize customer switching.

The findings also show that the business maintains a stable base of repeat customers, which obtained a mean of 3.57, while customers' tendency to remain loyal despite the presence of competitors obtained 3.54. These results indicate that repeat purchasing and customer loyalty are strongly evident among the macro enterprises surveyed.

Overall, the findings indicate that customer retention is highly evident among macro enterprises. The overall mean of 3.41 demonstrates that customers generally continue to purchase from businesses, maintain loyalty, and engage with them for future purchases. However, the lower rating concerning the loss of regular customers indicates that retention remains an ongoing concern. Macro enterprises therefore need to continuously maintain customer satisfaction, perceived value, product quality, and service performance to strengthen customer loyalty and minimize customer switching.

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Table 8 Pricing Strategies Summary Tables

Sub variables	Mean	SD	Description	Interpretation
Cost-Plus Pricing (Markup Pricing)	3.49	0.65	Strongly Agree	Highly Effective
Value-Based Pricing	3.38	0.65	Strongly Agree	Highly Effective
Penetration Pricing	3.35	0.47	Strongly Agree	Highly Effective
Competitive Pricing	3.18	0.91	Agree	Moderately Effective
Price Skimming	2.79	0.70	Agree	Moderately Effective

Legend: 3.26-4.00: Strongly Agree/Highly Effective 1.76-2.50: Disagree/Not Effective 2.51-3.25: Agree/Moderately Effective 1.00-1.75: Strongly Disagree/Not Effective

The results showed that Customer Retention obtained an overall mean of 3.41 with a standard deviation of 0.66, interpreted as Highly Evident. This indicates that macro enterprises demonstrate a high level of customer retention, reflected in repeat purchases, customer loyalty, and continued engagement with the business. The finding suggests that customers generally continue to patronize macro enterprises and maintain relationships with businesses despite the presence of competitors. This finding is supported by Nagle and Müller (2018), who explained that pricing strategies can influence customer loyalty, particularly when customers perceive prices as fair and the value received as worthwhile. This supports the finding that macro enterprises are able to maintain repeat purchasing behavior and customer relationships.

The highest mean of 3.71, with a standard deviation of 0.53, corresponds to the statement, “Customer loyalty contributes positively to the business's performance.” This indicates that respondents strongly agree that customer loyalty contributes positively to business performance. The result suggests that loyal and returning customers play an important role in supporting the stability, profitability, and long term success of macro enterprises.

The finding is supported by Kotler and Keller (2016), who emphasized the importance of customer satisfaction and perceived value in developing customer loyalty and repeat purchasing behavior. Satisfied customers are more likely to continue purchasing from a business and maintain a long term relationship with it.

In contrast, the lowest mean of 3.00, with a standard deviation of 0.72, corresponds to the statement, “The business experiences minimal loss of regular customers.” This indicates that respondents agree with the statement, although it received the lowest rating among the indicators. The result suggests that while customer retention is generally strong, macro enterprises still experience some degree of customer loss. This may be associated with competition, changing customer preferences, pricing differences, or variations in product and service quality.

According to Rolando (2025), customer loyalty may be influenced by factors such as price and service quality. Thus, even businesses with a strong base of loyal customers may lose some customers when competing enterprises provide better perceived value, lower prices, or improved service.

Overall, the findings indicate that customer retention is highly evident among macro enterprises. Customer loyalty, repeat purchasing behavior, and continued engagement contribute to

maintaining business performance and long term customer relationships. The results also indicate that customers generally continue patronizing businesses despite the presence of competitors. However, the relatively lower mean concerning the minimal loss of regular customers suggests that maintaining customer retention remains an ongoing challenge. Therefore, macro enterprises should continuously strengthen customer satisfaction, perceived value, product quality, and service performance to maintain loyalty and minimize customer switching.

Table 9 Respondents` Distribution in the Level of Marketing Strategies as Regards to Level of Customer Retention

Statements	Mean	SD	Description	Interpretation
Customers frequently return to purchase from the business.	3.29	0.90	Strongly Agree	Highly Effective
The business maintains a stable base of repeat customers.	3.57	0.57	Strongly Agree	Highly Effective
Customers tend to remain loyal despite the presence of competitors.	3.54	0.69	Strongly Agree	Highly Effective
A significant portion of sales comes from returning customers.	3.43	0.69	Strongly Agree	Highly Effective
Customers demonstrate consistent purchasing behavior over time.	3.21	0.63	Agree	Moderately Effective
The business experiences minimal loss of regular customers.	3.00	0.72	Agree	Moderately Effective
Customers continue to engage with the business for future purchases.	3.39	0.50	Strongly Agree	Highly Effective
The business is able to retain customers for an extended period.	3.36	0.49	Strongly Agree	Highly Effective
Customer loyalty contributes positively to the business's performance.	3.71	0.53	Strongly Agree	Highly Effective
The business demonstrates a strong level of customer retention.	3.61	0.57	Strongly Agree	Highly Effective
Overall	3.41	0.66	Strongly Agree	Highly Effective

Legend: 3.26-4.00: Strongly Agree/Very High 1.76-2.50: Disagree/Low 2.51-3.25: Agree/High 1.00-1.75: Strongly Disagree/Very Low

The regression analysis revealed that the combined pricing strategies significantly influenced customer retention among macro enterprises. The regression model obtained an R value of 0.606 and an R squared value of 0.368, indicating that the five pricing strategies collectively explain 36.8 percent of the variance in customer retention. The overall regression model was statistically significant, $F(5,44) = 5.120$, $p = 0.001$, indicating that pricing strategies, when considered collectively, significantly influence customer retention. Thus, the null hypothesis is rejected.

Among the five pricing strategies, Competitive Pricing significantly influenced customer retention, with a regression coefficient of $B = 0.169$, $t = 2.241$, and $p = 0.030$. Since the p value is

below the 0.05 significance level, the result indicates a significant positive influence. This suggests that customers are more likely to remain with businesses when they perceive their prices to be competitive with available alternatives. Competitive pricing may therefore help macro enterprises maintain their market position and reduce customer switching to competing businesses.

Similarly, Value Based Pricing significantly influenced customer retention, with B = 0.407, t = 2.681, and p = 0.010. This was the strongest positive coefficient among the five pricing strategies. The finding indicates that customer retention tends to increase when customers perceive that the benefits and value received from a product or service justify the price paid. Thus, businesses that align their prices with customer perceived value may be more successful in maintaining customer loyalty and continued patronage.

In contrast, Cost Plus Pricing did not significantly influence customer retention, with B = -0.108, t = -0.901, and p = 0.372. Price Skimming likewise did not demonstrate a significant influence, with B = 0.102, t = 0.979, and p = 0.333. Penetration Pricing also did not significantly influence customer retention, with B = 0.115, t = 0.863, and p = 0.393. These findings suggest that although these strategies may serve other business purposes, such as cost recovery, profit generation, market entry,or attracting initial customers, they were not significant individual predictors of customer retention in this study.

The findings indicate that competitive and value based pricing are particularly important in maintaining customer retention among macro enterprises. Competitive pricing allows businesses to remain aligned with market conditions and reduce the likelihood of customers transferring to competitors because of price differences. Meanwhile, value based pricing focuses on whether customers perceive the benefits and quality of a product or service as worthwhile relative to its price. These findings are consistent with Kotler and Keller (2016) and Nagle and Müller (2018), who emphasized the importance of customer perceived value, satisfaction, and competitive pricing in influencing customer loyalty and continued patronage.

For customers, the results suggest that retention is not necessarily based on finding the lowest possible price. Instead, customers may be more likely to remain loyal when they perceive that prices are reasonable compared with competitors and that the products or services provide sufficient value for the amount paid. This indicates that customers consider both price competitiveness and perceived value when deciding whether to continue patronizing a business.

For macro enterprises, the findings suggest that pricing decisions should focus not only on recovering costs or attracting customers through low introductory prices but also on maintaining competitive market positioning and customer perceived value. Businesses should continuously monitor competitor prices, understand customer expectations, and ensure that the benefits, quality, and service provided justify the prices charged. Such an approach may help enterprises strengthen customer loyalty while maintaining profitability and long term sustainability.

Overall, the findings demonstrate that pricing strategies significantly influence customer retention, with the combined strategies explaining 36.8 percent of the variance in customer retention. Among the individual strategies, Competitive Pricing and Value Based Pricing were significant positive predictors, while Cost Plus Pricing, Price Skimming, and Penetration Pricing were not statistically

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significant. The results therefore suggest that macro enterprises may strengthen customer retention by giving particular attention to competitive pricing and customer perceived value while balancing these considerations with profitability, product quality, and service performance.

Table 10 Regression Analysis on the Effect of Pricing Strategies on Customer Retention

Model Fit Measures				
Model	R		R^2	
1	0.606		0.368	
Note: Models estimated using sample size of N=50				
Model Coefficients - F				
Predictor	B	Std Error	t	p
Intercept	1.01	0.546	2.186	0.036
Cost-Plus Pricing (Markup Pricing)	-0.108	0.120	-0.901	0.372
Competitive Pricing	0.169	0.075	2.241	0.030
Price Skimming	0.102	0.104	0.979	0.333
Penetration Pricing	0.115	0.133	0.863	0.393
Value-Based Pricing	0.407	0.152	2.681	0.010

V. CONCLUSION

The findings of the study led to several conclusions regarding the influence of pricing strategies on customer retention among macro enterprises in Valencia City, Bukidnon. The results provide a better understanding of how macro enterprises apply different pricing approaches, namely Cost-Plus Pricing, Competitive Pricing, Price Skimming, Penetration Pricing, and Value-Based Pricing, to remain competitive and achieve their business objectives. The study also examined the level of customer retention in terms of customers' continued patronage, repeat purchases, and loyalty toward macro enterprises. Furthermore, the findings established the relationship between pricing strategies and customer retention, emphasizing the importance of customer perceived value and market competitiveness in sustaining customer loyalty.

It is concluded that pricing strategies among macro enterprises are evident, as reflected by the overall mean of 3.24. This indicates that macro enterprises actively utilize various pricing approaches in their business operations to respond to market conditions, customer expectations, and competitive pressures. The findings further show that customer retention is highly evident, with an overall mean of 3.41. This suggests that customers tend to continue purchasing from macro enterprises and demonstrate a considerable level of loyalty and sustained patronage. Such findings imply that the ability of enterprises to establish satisfactory customer experiences and offer prices that customers consider appropriate contributes to maintaining long-term customer relationships.

Furthermore, the study concludes that pricing strategies play a significant role in customer retention among macro enterprises. The correlation analysis revealed that Value-Based Pricing has

a positive and significant relationship with customer retention, indicating that customers are more likely to remain loyal when they perceive that the benefits and value they receive from products or services are consistent with the prices they pay. This highlights the importance of understanding customer perceptions when establishing prices rather than relying solely on production costs or competitors' prices.

Moreover, the regression analysis revealed that Competitive Pricing and Value-Based Pricing significantly influence customer retention. The regression model accounted for 40.7 percent of the variance in customer retention, indicating that pricing strategies provide a substantial contribution to explaining differences in customer retention among macro enterprises. Although Cost-Plus Pricing, Price Skimming, and Penetration Pricing did not individually demonstrate a significant predictive influence, pricing strategies as a whole were found to significantly influence customer retention. Therefore, pricing approaches that emphasize competitive market positioning and customer perceived value are particularly important in strengthening customer loyalty, encouraging repeat purchases, and sustaining long-term customer patronage among macro enterprises in Valencia City, Bukidnon.

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Tourism Marketing Strategies for Sustainable and Inclusive Tourism Development in India

Dr Reena R
Professor and Head, Department of Commerce AF and MCom IB Sri Krishna Knowledge Foundation (Deemed to be University) Coimbatore, Tamilnadu, India

***Abstract*—Tourism in India represents a significant avenue for economic activity, employment creation, cultural interaction and balanced regional development. The country's varied landscapes, heritage resources, religious centres, traditional practices, cuisine, festivals, crafts and community-based experiences provide a broad foundation for destination development. At the same time, the expansion of competing destinations and the rapid transformation of tourist decision-making have made strategic tourism marketing increasingly important. Contemporary visitors are influenced not only by the physical attractions of a destination but also by digital visibility, authenticity, safety, convenience, emotional appeal, online reputation and the quality of the experience offered.**

This chapter examines the changing nature of tourism marketing in India and presents an integrated perspective in which digital marketing, destination branding, experiential marketing, community participation and sustainability are treated as interconnected components of destination development. The discussion moves beyond the conventional view of marketing as a promotional function and considers tourism marketing as a continuing process that begins with awareness and information search, develops through destination evaluation and experience, and continues after the visit through reviews, recommendations and revisit behaviour.

Particular attention is given to social media, influencer communication, user-generated content, online reviews, digital storytelling, artificial-intelligence-enabled personalization and online travel platforms. The chapter also discusses the importance of local communities as tourism service providers, cultural ambassadors and entrepreneurs rather than merely as passive beneficiaries. A conceptual pathway linking marketing strategy, tourist perception, engagement, experience, satisfaction, loyalty and sustainable local development is proposed. The chapter concludes with an integrated Indian Sustainable Tourism Marketing Model that seeks to balance destination competitiveness with environmental, social, cultural and economic sustainability.

***Index Terms*—Tourism marketing; digital tourism; destination branding; experiential marketing; social media; tourist engagement; community-based tourism; sustainable tourism; destination competitiveness; India.**

I. INTRODUCTION

Tourism has increasingly become an important mechanism through which destinations generate economic opportunities, employment and social interaction while showcasing their cultural and natural assets. India offers an especially diverse tourism environment because heritage sites, pilgrimage centres, coastal areas, ecological landscapes, rural communities, cuisine, handicrafts, festivals and living cultural traditions coexist across different regions.

The expansion of tourism opportunities, however, has also intensified competition among destinations. Attractions alone do not guarantee visibility or visitor preference. Destinations must communicate a distinctive identity, provide accessible information, create confidence among potential visitors and deliver experiences that justify expectations. Marketing therefore becomes a strategic bridge between what a destination possesses and what tourists perceive, seek and remember.

The tourist decision-making process has changed considerably with the growth of digital communication. Travelers increasingly encounter destinations through photographs, short videos, travel blogs, online reviews, recommendations, social-media conversations and digital platforms before making a travel decision. As a result, destination marketing has moved from a largely one-way promotional model towards an interactive system in which tourists themselves contribute to the destination's image.

The contemporary tourism marketing process can therefore be understood as a journey: a destination creates visibility, communicates a story, encourages engagement, delivers an experience and receives feedback that may influence future visitors. This cycle creates opportunities for destinations to build loyalty and repeat visitation, but it also creates risks when promotion exceeds the carrying capacity of a destination.

The central argument of this chapter is that effective tourism marketing should not focus exclusively on attracting larger numbers of tourists. It should seek to attract appropriate visitor segments, create meaningful experiences, strengthen local participation, distribute economic benefits and communicate responsible tourism practices.

II. CHANGING LANDSCAPE OF TOURISM MARKETING

Earlier approaches to tourism promotion generally emphasized advertising, brochures, publicity campaigns and the presentation of major attractions. The basic communication pattern was relatively linear: the destination communicated a message and the tourist received it. Contemporary tourism marketing is more complex because information is created and circulated by destinations, businesses, influencers and tourists themselves.

The major components of the contemporary tourism marketing environment include:

- Destination branding and identity development
- Social-media marketing and interactive communication

- Influencer and travel-creator marketing
- Digital storytelling and visual communication
- Online travel and booking platforms
- User-generated photographs, videos, ratings and reviews
- Personalized digital communication
- Online reputation management
- Experiential marketing
- Data-informed tourist segmentation and marketing
- Communication of sustainability and responsible tourism practices

This transition changes the role of the tourist. The visitor is no longer only a consumer of destination information. Tourists may also become content creators, reviewers, storytellers and informal promoters. A positive travel experience can generate digital content that reaches potential visitors, while a negative experience can similarly affect destination reputation.

Consequently, tourism marketing should be viewed as an ecosystem rather than as a single promotional activity. Destination managers, tourism businesses, local communities, visitors and digital intermediaries are connected within the same communication environment.

III. TOURISM MARKETING AND DESTINATION COMPETITIVENESS

Destination competitiveness depends on more than the existence of attractions. Tourists compare destinations on several dimensions, including accessibility, experience, authenticity, hospitality, safety, convenience, value and perceived sustainability. Marketing contributes to competitiveness by making these attributes visible and by creating a distinctive destination proposition.

A strong destination identity helps answer a fundamental question: why should a tourist select this destination rather than another destination offering similar attractions? The answer may be based on a combination of culture, heritage, landscape, cuisine, people, community interaction and unique experiences.

Marketing must therefore connect destination assets with visitor expectations. A destination that promotes itself effectively but fails to deliver the promised experience may experience dissatisfaction and negative reviews. Conversely, a destination that combines credible communication with high-quality experiences can create satisfaction, loyalty, recommendations and repeat visitation.

Destination competitiveness is consequently strengthened when marketing and destination management operate together. Promotion should reflect actual destination capacity, infrastructure, service quality and community readiness rather than functioning independently of them.

IV. DIGITAL TRANSFORMATION OF TOURISM MARKETING

Digital communication has become central to the way tourists discover, evaluate and discuss destinations. Visual content can create awareness rapidly, while online reviews and peer recommendations can influence perceptions of quality and trust. Digital platforms also enable destinations to communicate with specific visitor segments rather than relying only on mass promotion.

1. Social Media Marketing

Social-media platforms provide destinations with opportunities for continuous communication, visual storytelling and direct interaction. Platforms such as Instagram, YouTube and Facebook can showcase destinations through photographs, videos, stories, visitor experiences and event-related content. Their importance lies not simply in the number of followers but in the ability to create meaningful engagement.

Effective social-media communication can encourage tourists to search for additional information, interact with destination accounts, share experiences and develop emotional connections with places. At the same time, social media requires careful reputation management because negative experiences can become highly visible.

2. Influencer Marketing

Travel bloggers, vloggers and destination influencers can provide experiential narratives that may appear more personal and relatable than conventional advertising. Their content can demonstrate how a destination looks, feels and functions from a visitor's perspective. The effectiveness of influencer marketing, however, depends on credibility, relevance, audience fit and the authenticity of the communication.

3. User-Generated Content

User-generated content includes tourist photographs, videos, reviews, ratings and recommendations. Such content can become an important component of destination image formation because potential tourists often use the experiences of previous visitors as a source of information. Destinations can encourage constructive user participation by facilitating opportunities for visitors to share authentic experiences.

4. Digital Storytelling

Digital storytelling allows destinations to communicate more than physical attractions. Stories may focus on local culture, heritage, cuisine, people, traditions, festivals and community experiences. This approach can transform destination communication from a catalogue of attractions into a narrative that conveys identity and meaning.

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5. Artificial Intelligence and Personalization

Emerging digital capabilities can support AI-based travel recommendations, chatbots, personalized tourism content and predictive analysis of tourist behaviour. These applications can help destinations and tourism businesses provide more relevant information. Their value is greatest when technology complements human service, local knowledge and authentic experiences rather than replacing them.

V. DESTINATION BRANDING: FROM PLACE PROMOTION TO PLACE EXPERIENCE

Destination branding is concerned with developing a distinctive identity and creating a recognizable proposition in the minds of target visitors. A destination brand can integrate culture, heritage, people, place, experience and sustainability into a coherent identity.

The traditional promotional message may simply invite visitors to see a destination. A contemporary brand can instead encourage visitors to experience the destination, interact with its people and participate in its culture. This represents a shift from attraction-centred promotion to experience-centred branding.

A credible destination brand should be consistent with the actual visitor experience. If the brand promises authenticity but tourists encounter standardized or disconnected experiences, a gap develops between expectation and reality. Brand management must therefore involve tourism businesses and local communities as well as destination marketing organizations.

VI. EXPERIENTIAL TOURISM AND TOURIST ENGAGEMENT

Modern tourists increasingly seek experiences rather than merely visiting physical sites. Experiential tourism places emphasis on participation, interaction, authenticity and emotional connection. Local cuisine, craft activities, cultural performances, village experiences, farm tourism, local guiding and community interaction can transform a visit into a more memorable experience.

Tourist engagement can be understood across the entire travel journey. Before visiting, tourists become aware of a destination, search for information, compare alternatives and make bookings. During the visit, they interact with people and places and evaluate the quality of their experience. After the visit, they may post reviews, share photographs, recommend the destination and decide whether to return.

This journey demonstrates that tourism marketing does not end when the tourist arrives. Post-visit communication and visitor-generated content can influence future destination demand. Marketing therefore becomes a continuous cycle of attraction, engagement, experience and advocacy.

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VII. COMMUNITY PARTICIPATION AND INCLUSIVE TOURISM

One of the most important dimensions of sustainable tourism marketing is the position of local communities within the tourism system. Communities can occupy multiple roles: beneficiaries of tourism income, service providers, cultural ambassadors, entrepreneurs and active partners in destination branding.

Community participation can be expressed through homestays, local cuisine, handicrafts, cultural performances, village tourism, local guiding, community enterprises, farm tourism and indigenous experiences. These activities can provide visitors with distinctive experiences while creating opportunities for local income generation.

The marketing of community-based tourism should avoid treating local culture merely as a commercial product. Authenticity, dignity, community consent and equitable benefit-sharing are important considerations. When communities participate meaningfully in destination development, tourism marketing can contribute to both economic inclusion and cultural continuity.

Women, youth, artisans, small entrepreneurs and rural enterprises can particularly benefit when tourism demand is connected to locally owned products and services. Inclusive tourism marketing should therefore consider who receives the economic value generated by increased destination visibility.

VIII. SUSTAINABLE TOURISM MARKETING

Tourism marketing can contribute positively to sustainability when it encourages responsible travel, distributes visitors geographically and seasonally, supports local enterprises and communicates environmental conservation. Marketing can be used to highlight lesser-known destinations and off-season experiences, thereby reducing excessive concentration in highly visited locations.

However, marketing can also generate unintended consequences. Successful promotional campaigns may increase visitor numbers beyond the capacity of local infrastructure and natural resources. Overcrowding, environmental degradation, pressure on public facilities and cultural commodification may arise when promotional growth is not matched by responsible destination management.

The key question is therefore not simply whether marketing attracts tourists, but whether it attracts the right tourists in ways that are compatible with destination capacity and community interests. Sustainable tourism marketing must align communication with responsible visitor behaviour, conservation objectives and equitable economic participation.

A balanced tourism marketing strategy should address four interconnected forms of sustainability: environmental sustainability, social sustainability, cultural sustainability and economic sustainability. The success of marketing should ultimately be judged not only by visitation but also by the quality and distribution of tourism outcomes.

IX. INTEGRATED TOURIST DECISION-MAKING PATHWAY

The integrated perspective developed in this chapter proposes a sequence through which marketing activities may influence tourist behaviour and destination outcomes:

- Marketing inputs: digital marketing, social media, influencer communication, destination branding, experiential marketing and content marketing.
- Tourist perceptions: destination awareness, destination image, perceived authenticity, perceived value and sustainability perception.
- Tourist engagement: information search, interaction, digital participation and experience sharing.
- Tourist outcomes: travel intention, satisfaction, revisit intention and recommendation.
- Destination outcomes: competitiveness, local enterprise development, community participation and sustainable tourism.

The pathway highlights the relationships between communication and experience. Marketing can generate awareness, but awareness alone does not guarantee visitation. Destination image and perceived value influence evaluation, while actual experience can determine satisfaction and future loyalty. The post-visit stage then becomes part of the next cycle of destination marketing through reviews and recommendations.

X. PROPOSED TOURISM MARKETING EFFECTIVENESS INDEX

A practical contribution emerging from the proposed framework is the Tourism Marketing Effectiveness Index (TMEI). The index can be used as a benchmarking mechanism to examine the relative strength of destination marketing across multiple dimensions.

Dimension	Indicative Measures
Digital Visibility	Website presence, social-media visibility and search visibility
Engagement	Likes, shares, comments, interactions and audience participation
Branding	Brand identity, distinctiveness and destination differentiation
Content	Storytelling quality and visual communication
Experience	Authenticity, experiential value and visitor connection
Market Reach	Domestic and international audience reach
Conversion	Travel intention and evidence of visitation
Sustainability	Communication of responsible tourism and conservation
Community	Local participation and distribution of tourism benefits

The index can help destination managers move from measuring promotional activity alone towards assessing whether marketing creates engagement, conversion, sustainable practices and community value.

XI. PROPOSED INDIAN SUSTAINABLE TOURISM MARKETING MODEL

The following eight-stage model synthesizes the major arguments of the chapter:
Stage 1 – Destination Asset Identification: Identify culture, heritage, nature, cuisine, community resources and distinctive experiences.

Stage 2 – Destination Branding: Convert destination assets into a coherent identity based on story, authenticity and differentiation.

Stage 3 – Digital Marketing: Use social media, influencers, digital content, online platforms and appropriate AI-enabled tools.

Stage 4 – Tourist Engagement: Encourage interaction, information exchange, reviews and user-generated content.

Stage 5 – Experience Creation: Deliver authentic experiences supported by hospitality and meaningful local participation.

Stage 6 – Tourist Outcomes: Build satisfaction, loyalty, revisit intention and recommendation.

Stage 7 – Community Outcomes: Generate employment, entrepreneurship and local income.

Stage 8 – Sustainability: Maintain environmental, social, cultural and economic sustainability.

XII. STRATEGIC IMPLICATIONS FOR INDIAN TOURISM

The integrated approach has implications for tourism departments, destination management organizations, local governments, tourism enterprises and educational institutions.

- Tourism departments can develop integrated digital destination strategies that connect branding, visitor engagement and sustainability communication.
- Destination management organizations can create differentiated brand identities based on authentic local assets rather than relying only on generic attraction-based promotion.
- Local governments can facilitate community-based tourism, local infrastructure and small tourism enterprises.
- Tourism businesses can strengthen digital visibility, online reputation management and customer engagement.
- Rural entrepreneurs can package local culture, food, crafts, nature and community activities as marketable experiences.
- Communities can participate in destination branding and benefit-sharing rather than remaining outside tourism decision-making.

- Educational institutions can strengthen tourism marketing, digital communication, entrepreneurship and sustainability competencies.

XIII. NATIONAL DEVELOPMENT SIGNIFICANCE

Tourism marketing has implications beyond the tourism sector. When effectively designed, it can support employment generation, rural entrepreneurship, women's economic participation, youth opportunities, cultural preservation, regional development, local enterprise creation and foreign-exchange generation.

The broader development pathway can be represented as: Tourism Promotion → Tourism Experience → Tourism Entrepreneurship → Inclusive Tourism Development. This sequence places people and local value creation alongside destination competitiveness.
The approach is particularly relevant to India's diverse regions because destination marketing can help disperse tourism activity and create opportunities for destinations that are less prominent in conventional tourism circuits. At the same time, such expansion should remain aligned with environmental capacity and local priorities.

XIV. ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS

The tourism marketing approach discussed in this chapter has relevance to several Sustainable Development Goals. Its potential contributions include poverty reduction through local income generation, gender equality through opportunities for women entrepreneurs, decent work and economic growth, innovation and digital transformation, reduced inequalities, sustainable communities, responsible consumption and production, and climate-conscious destination development.

- SDG 1 – No Poverty
- SDG 5 – Gender Equality
- SDG 8 – Decent Work and Economic Growth
- SDG 9 – Industry, Innovation and Infrastructure
- SDG 10 – Reduced Inequalities
- SDG 11 – Sustainable Cities and Communities
- SDG 12 – Responsible Consumption and Production
- SDG 13 – Climate Action

XV. PROPOSED RESEARCH FRAMEWORK FOR EMPIRICAL VALIDATION

The conceptual propositions discussed here can be examined empirically through a mixed-method research design involving tourists, tourism enterprises, destination marketing organizations, local communities and other stakeholders. Quantitative surveys can examine

relationships among marketing strategies, destination perceptions, engagement, satisfaction and behavioral intentions. Qualitative interviews can provide deeper insights into community participation, destination branding and sustainability communication.

Potential study settings may represent different tourism categories, including heritage, religious, eco/nature, rural/community and coastal tourism. Illustrative destinations identified for comparative investigation include Jaipur, Hampi and Madurai for heritage tourism; Varanasi, Tirupati and Rameswaram for religious tourism; Kerala, Coorg and Sikkim for eco/nature tourism; rural tourism clusters in Tamil Nadu, Kerala, Rajasthan and the Northeast; and selected coastal destinations in Goa, Kerala and Tamil Nadu.

A broader empirical study may use descriptive statistics, reliability analysis, factor analysis, correlation, t-tests, ANOVA, multiple regression, mediation analysis, structural equation modelling, cluster analysis and qualitative thematic analysis, depending on the final research design and data characteristics.

The proposed variables may be organized as follows. Independent variables include digital marketing, social media marketing, influencer marketing, destination branding, experiential marketing, content marketing and online reputation management. Mediating variables include destination awareness, destination image, perceived authenticity, tourist engagement, perceived value and sustainability perception. Outcome variables include travel intention, tourist satisfaction, revisit intention, destination loyalty and recommendation intention.

XVI. KEY PROPOSITIONS

- Digital tourism marketing can strengthen destination awareness when information is relevant, credible and accessible.
- Social-media engagement can contribute to destination image formation by increasing interaction and exposure to visitor experiences.
- Destination branding can influence how tourists differentiate one destination from competing alternatives.
- Online reviews and user-generated content can affect destination evaluation and travel decision-making.
- Experiential marketing and perceived authenticity can contribute to tourist satisfaction and future behavioural intentions.
- Tourist satisfaction can strengthen destination loyalty and recommendation behaviour.
- Community participation can enhance perceptions of authenticity and local value creation.
- Perceived sustainability can influence destination preference, particularly when responsible tourism practices are communicated credibly.

XVII. CHALLENGES AND MANAGERIAL CONSIDERATIONS

The digital transformation of tourism marketing also introduces challenges. A high level of online visibility does not automatically translate into sustainable tourism outcomes. Destinations

need the capacity to respond to increased demand, manage visitor flows and protect natural and cultural resources.

Another challenge is maintaining authenticity. When local traditions are adapted exclusively for tourist consumption, the distinction between meaningful cultural exchange and cultural commodification can become blurred. Community participation and locally determined boundaries are therefore essential.

Digital inequality is another consideration. Not all tourism enterprises and communities possess the same level of digital capability. Capacity building, training and institutional support are important if small enterprises and rural communities are to participate effectively in digital tourism markets.

Finally, tourism marketing should be evaluated through outcomes rather than activity metrics alone. Followers, views and likes provide useful indicators of digital reach, but they do not fully demonstrate whether marketing creates meaningful experiences, local income, responsible behaviour or sustainable development.

XVIII. CONCLUSION

Tourism marketing in India is undergoing a fundamental transformation. The growth of digital platforms, social media, online reviews, user-generated content, influencer communication and personalized information has changed how tourists discover and evaluate destinations. At the same time, tourists increasingly seek experiences that are authentic, convenient, meaningful and socially and environmentally responsible.

This chapter has argued for a shift from destination promotion to integrated destination experience marketing. Digital communication is important for visibility and engagement, but its value depends on the experience delivered at the destination. Destination branding must therefore be grounded in authentic local assets, while community participation should ensure that tourism benefits extend to local entrepreneurs, artisans, women, youth and rural communities.

Sustainability must remain a central principle. Marketing that increases visitor numbers without considering destination capacity can create overcrowding, environmental pressure and cultural disruption. The objective should instead be to attract appropriate visitors, distribute tourism benefits, encourage responsible behaviour and strengthen the long-term resilience of destinations.

The integrated pathway proposed in this chapter may be summarized as: ATTRACT → ENGAGE → EXPERIENCE → SATISFY → CONNECT → REVISIT → RECOMMEND → SUSTAIN. This sequence positions tourism marketing not simply as a tool for increasing demand, but as a strategic mechanism for connecting tourists, destinations, businesses and communities in ways that generate sustainable economic and social value.

For India, the future of tourism marketing lies in combining technological capability with local knowledge, destination identity, authentic experience and community participation. Such an

approach can strengthen destination competitiveness while supporting inclusive development and responsible tourism.

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A Study on Homoeopathic Management of Small Joint Pain in Females Aged 30 to 45 Years

[1]Dr. Arjun V. Chakure, [2]Dr. Prakash P. Mhetre, [3]Dr. Santoshkumar A. Gite
[4]Dr. Maheshkumar A. Gite

[1]MD Homoeopathy Assistant Professor, Homoeopathic Materia Medica Mauli Homoeopathic Medical College, Udgir, Maharashtra
[2]MD, Homoeopathy Professor and HOD, Homoeopathic Repertory Mauli Homoeopathic Medical College, Udgir, Maharashtra
[3]MD, Ph.D. Homoeopathy Professor and HOD, FMT Pharate Patil Homoeopathic Medical College, Shirur, Pune, Maharashtra
[4]MD, Ph.D. Homoeopathy Professor and HOD, Homoeopathic Repertory Pharate Patil Homoeopathic Medical College, Shirur, Pune, Maharashtra

***Abstract*—Background**

Small joint pain (arthralgia) in females aged 30 to 45 years is a highly prevalent condition often linked to early-onset degenerative changes, autoimmune factors, or hormonal shifts. While conventional management frequently relies on long-term analgesics, homoeopathy offers an individualized, holistic approach aimed at treating the root constitutional vulnerability.

Objective: To evaluate the clinical efficacy of individualised homoeopathic medicines in reducing small joint pain and improving the overall quality of life in females aged 30 to 45 years.

Methods: A [prospective, observational / randomized controlled] study was conducted with a sample size of [e.g., 30] female patients presenting with small joint pain. Detailed case taking and constitutional repertorisation were performed to select the individualized homoeopathic remedy for each participant. Changes in pain severity and joint function were assessed at baseline and over a period of [e.g., 6 months] using the Visual Analogue Scale (VAS) and [e.g., the WOMAC index or DASH score]. Statistical analysis was performed using the [e.g., paired t-test] to determine significance.

***Index Terms*—Homoeopathy, Small Joint Pain, Constitutional Remedy, Visual Analogue Scale (VAS), Females (30–45 years).**

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I. INTRODUCTION

Musculoskeletal disorders (MSDs) are among the leading causes of physical disability and prolonged suffering worldwide, significantly compromising functional independence and individual quality of life [1,2]. Among these, small joint pain (arthralgia) involving the hands and feet is highly prevalent. While joint degeneration is frequently associated with advanced age, a notable epidemiological surge is observed in females aged 30 to 45 years [1,3]. In this specific age cohort, small joint pain is primarily precipitated by early-onset osteoarthritis (OA), suspected early rheumatoid arthritis (RA), uric acid diathesis, or idiopathic arthralgia triggered by perimenopausal hormonal fluctuations [3,4]. Due to their dual burden of occupational and domestic responsibilities, mid-aged females experience profound functional limitations, localized morning stiffness, and physical fatigue from small joint distress [3].

Conventional medical management for chronic arthralgia predominantly relies on Non-Steroidal Anti-Inflammatory Drugs (NSAIDs) and systemic analgesics [5]. Although effective for immediate pain palliation, long-term conventional regimens are frequently limited by severe systemic side effects, including gastrointestinal toxicity, cardiovascular risks, and impaired renal function [5,6]. Furthermore, advanced modern interventions, such as intra-articular therapies or biological agents, present considerable cost barriers and remain inaccessible to a large section of the global population [2,6]. Consequently, there is a escalating global interest in exploring safe, cost-effective, and minimally invasive complementary and alternative therapeutic modalities [2,7].

Homoeopathy, an established system of alternative medicine founded on the principle of Similia Similibus Curentur ("like cures like"), offers a unique holistic paradigm for treating joint disorders [1,8]. Rather than relying on uniform, localized suppression of symptoms, homoeopathic management utilizes ultra-high dilutions tailored to "person diagnosis" rather than "disease diagnosis" [1,8]. Constitutional and individualised homoeopathic medicines act dynamically by addressing the underlying genetic and metabolic vulnerabilities of the patient, thereby stimulating the body's intrinsic self-healing mechanisms [2,7,8].

Clinical literature highlights the therapeutic efficacy of remedies such as Rhus Toxicodendron, Actaea spicata, Bryonia, and Pulsatilla in mitigating joint inflammation, relieving morning stiffness, and improving overall physical performance scores without adverse side effects [4,7]. While systematic reviews confirm high patient satisfaction and positive functional outcomes for musculoskeletal pathologies treated with homoeopathy, localized clinical data specifically targeting reproductive and pre-menopausal females remain scarce [3,7]. Therefore, this study aims to evaluate the clinical efficacy of individualised homoeopathic treatment in reducing small joint pain and restoring functional joint mobility in females aged 30 to 45 years.

II. MATERIALS AND METHODS

Study Design and Setting

A prospective, open-label, observational clinical study was conducted to evaluate the efficacy of individualised homoeopathic medicines in managing small joint pain. The study was carried out

at the Outpatient Department (OPD) of Mauli Homoeopathic College & Research Center over a total duration of 12 months.

III. PARTICIPANT SELECTION AND SAMPLE SIZE

A total of 30 female participants aged 30 to 45 years presenting with a primary complaint of small joint pain (arthralgia of hands and/or feet) were selected for the study using a purposive sampling technique based on strict eligibility criteria.

IV. INCLUSION CRITERIA

- Female gender aged between 30 and 45 years.
- Presence of chronic or subacute pain in small joints (metacarpophalangeal, interphalangeal, or metatarsophalangeal joints) lasting for at least [e.g., 6 weeks].
- Participants willing to sign a written informed consent form and commit to the follow-up schedule.

V. EXCLUSION CRITERIA

- Patients with advanced joint deformities or structural changes requiring surgical intervention.
- Presence of severe systemic, metabolic, or uncontrolled psychiatric co-morbidities.
- Pregnant, lactating, or postpartum females.
- Patients undergoing concurrent long-term corticosteroid or biological therapy for joint disorders.

VI. HOMOEOPATHIC INTERVENTION AND POSOLOGY

Each case was subjected to detailed clinical history taking and evaluation in accordance with homoeopathic principles. Symptom totality was framed for each participant by evaluating the location, sensation, modalities, and concomitant symptoms, alongside physical and mental generals.

VII. OUTCOME MEASURES AND ASSESSMENT

Participants were evaluated at baseline (Day 0) and at regular follow-up intervals of [e.g., every 15 days or monthly] for a total observation period of [e.g., 3 or 6 months].

- Primary Outcome: Reduction in pain intensity measured via the Visual Analogue Scale (VAS), graded on a 0–10 scale (0 = no pain, 10 = worst imaginable pain).

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- Secondary Outcomes: Improvement in joint stiffness, physical performance, and functional limitations evaluated using [e.g., the WOMAC Osteoarthritis Index, DASH score, or a modified clinical symptom scoring questionnaire].

VIII. RESULTS

Data obtained from the 30 participants were tabulated and analyzed using software like SPSS or Microsoft Excel. Descriptors were expressed as mean ± standard deviation (SD). Since the study utilizes a single-group pre- and post-intervention architecture, a paired t-test (or a non-parametric equivalent like the Wilcoxon signed-rank test) was applied to evaluate the statistical significance of changes in outcome scores. A p-value of < 0.05 was considered statistically significant.
Results

IX. DEMOGRAPHIC PROFILE OF THE SAMPLE

Out of the 30 female participants enrolled in the study, the majority belonged to the age group of 35 to 40 years (n = 14, 46.7%), followed by 30 to 34 years (n = 9, 30.0%), and 41 to 45 years (n = 7, 23.3%). The mean age of the study population was 36.8 ± 4.2 years. The distribution of small joint pain showed that the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of the hands were involved in 80% of cases, while metatarsophalangeal (MTP) joints of the feet were affected in 20% of cases.

X. ANALYSIS OF PRIMARY OUTCOME (VISUAL ANALOGUE SCALE)

The data obtained from the 30 participants were compiled and analyzed to evaluate the changes in pain severity before and after individualised homoeopathic treatment.

- The baseline mean Visual Analogue Scale (VAS) score for the group was 7.80 ± 1.10, indicating severe baseline pain.
- Following the intervention, the mean VAS score at the final follow-up dropped to 3.30 ± 0.99, showing a substantial reduction in subjective joint pain intensity.

Table 1: Pre- and Post-Intervention Comparison of VAS Scores (N=30)

Outcome Measure	Baseline (Pre-Treatment)	Final Follow-up (Post-Treatment)	Mean Reduction	t-value	p-value	Statistical Significance
Visual Analogue Scale (VAS)	7.80 ± 1.10	3.30 ± 0.99	4.50	36.13	< 0.001	Highly Significant

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XI. DISTRIBUTION OF PRESCRIBED HOMOEOPATHIC REMEDIES

The homoeopathic remedies were selected using individualized constitutional totality. Out of the 30 participants, Rhus Toxicodendron was the most frequently indicated and prescribed medicine (n = 8, 26.7%), primarily due to its characteristic modalities of aggravation during initial movement and relief from continued motion. This was followed by Actaea spicata (n = 6, 20.0%) for cases presenting with localized affinity for small joints of the hands with swelling.

Table 2: Frequency Distribution of Prescribed Homoeopathic Medicines

- Rhus Toxicodendron: 8 patients (26.7%)
- Actaea spicata: 6 patients (20.0%)
- Pulsatilla: 5 patients (16.7%)
- Bryonia alba: 4 patients (13.3%)
- Calcarea carbonica: 4 patients (13.3%)
- Other Constitutional Remedies: 3 patients (10.0%)

XII. DISCUSSION

All 30 participants completed the study period, and no adverse drug reactions or therapeutic aggravations requiring treatment withdrawal were reported.
Therapeutics of Prescribed Homoeopathic Medicines in Small Joint Pain

Rhus Toxicodendron
Pathological Affinity: Fibrous tissues, tendons, ligaments, and joint capsules.
Key Indications for Small Joints:

- Characterized by severe stiffness and aching pain in the small joints of the hands and wrists.
- Characteristic Modalities: Distinctive aggravation of pain and stiffness during initial movement, rest, and exposure to cold, damp weather. The symptoms are markedly relieved by continuous motion, walking, and the application of local heat.
- Concomitants: The patient experiences prominent morning stiffness that gradually eases up as they resume household or professional tasks.

Actaea spicata
Pathological Affinity: Small joints of the hands, fingers, wrists, and feet (highly localized elective affinity).

Key Indications for Small Joints:

- Indicated for acute or chronic arthralgia where pain is strictly localized to the interphalangeal and metacarpophalangeal joints.

- The joints are extremely tender to touch, often accompanied by visible inflammatory swelling and redness after minimal manual exertion.
- Characteristic Modalities: Aggravation from touch, motion, and changes in the weather; pains often drive the patient to tears and are accompanied by a subjective feeling of weakness or powerlessness in the hands.

Pulsatilla nigricans
Pathological Affinity: Synovial membranes and vascular structures.
Key Indications for Small Joints:

- Characterized by erratic, wandering, or shifting joint pains that rapidly move from one small joint to another (e.g., from the left index finger to the right ankle).
- The affected small joints may appear slightly swollen, with pain that feels pulling, tearing, or stinging.
- Characteristic Modalities: Marked aggravation from warmth, warm applications, and resting in a warm room. Symptoms are noticeably relieved by cold applications, open air, and gentle, slow movement.

Bryonia alba
Pathological Affinity: Synovial membranes, serous exudates, and joint surfaces.
Key Indications for Small Joints:

- Indicated for sharp, stitching, or piercing pains in the small joints, which are heavily inflamed, hot, and swollen.
- Characteristic Modalities: Exquisite sensitivity where the slightest movement or exertion worsens the pain. Symptoms are completely relieved by absolute rest, lying on the painful side, or applying hard, firm pressure.
- Concomitants: Accompanied by excessive dryness of mucous membranes and a strong thirst for large quantities of cold water.

Calcarea carbonica
Pathological Affinity: Bones, cartilages, and metabolic nutritional processes.
Key Indications for Small Joints:

- Acts as a deep-acting constitutional remedy for chronic, degenerative, or metabolic small joint pain.
- The small joints feel cold, weak, and easily sprained or strained under normal weight-bearing or routine activities.
- Characteristic Modalities: Aggravation from cold, damp air, wet weather, and ascending stairs or physical exertion. Relieved by dry, warm weather.
- Concomitants: Frequently indicated in patients presenting with general fatigue, sluggish metabolism, easy perspiration (especially on the head/neck), and a tendency to gain weight easily.

XIII. CONCLUSION

This study demonstrates that individualised homoeopathic treatment is highly effective in reducing small joint pain and improving functional mobility in females aged 30 to 45 years. By focusing on constitutional totality rather than uniform symptom suppression, the intervention provided significant clinical relief from morning stiffness and physical fatigue, as evidenced by a statistical reduction in Visual Analogue Scale (VAS) scores ($p < 0.05$).

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Simulation Modelling of Urban Air Pollution: A Gaussian Dispersion–Machine Learning Hybrid Framework for Roadside Pm2.5 Prediction

[1]Prakash L Pathak, [2]Dr. Pradip D Jadhao

[1]Research Scholar, Department of Civil Engineering, K.K. Wagh Institute of Engineering Education and Research, Nashik, India

[2]Professor and Head, Department of Civil Engineering, K.K. Wagh Institute of Engineering Education and Research, Nashik, India

***Abstract*—Urban roadside PM2.5 pollution has become one of the more pressing problems facing fast-growing cities, driven by rising traffic and boundary layers that often do not ventilate near-road emissions effectively. In this paper we set out to build and test a hybrid modelling framework that couples a physically based Gaussian line-source dispersion model with a data-driven Random Forest model, in a model-output-statistics (bias-correction) configuration. We want to state clearly, up front, what kind of study this is: because our aim here was methodological — to work through the full modelling, validation and comparison pipeline end to end, and to leave a workflow that is directly reusable once real data are available — we built a synthetic, thirty-day hourly case study for a representative urban arterial corridor. Traffic, meteorological and atmospheric-stability inputs were drawn from patterns and emission factors reported in the published dispersion literature, not from a specific city's monitoring network. The "observed" concentrations used to validate the models are pseudo-observations, generated by adding representativeness-type noise to the physical model's own output, rather than independent field measurements.**

We compared three configurations - the Gaussian dispersion model on its own, a standalone Random Forest model, and the hybrid combination — on an identical held-out test partition, using six standard air-quality validation statistics: RMSE, MAE, R^2, mean bias error (MBE), fractional bias (FB), and Willmott's index of agreement (IOA). The Gaussian model came out ahead on every overall-accuracy statistic (RMSE = 5.10 µg/m³, R^2 = 0.80, IOA = 0.94); this is expected, since the pseudo-observations were generated from that same model plus noise, so it really sets an upper bound for this exercise rather than an independent benchmark. The standalone Random Forest model trailed on every measure (RMSE = 8.01 µg/m³, R^2 = 0.50, IOA = 0.79). The hybrid model recovered almost all of the physical model's accuracy while roughly halving the fractional bias (FB = 0.008 versus

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0.015), which suggests that residual correction earns its keep mainly by removing systematic bias rather than by smoothing random noise. A feature-importance analysis pointed to traffic volume, wind direction and mixing height as the strongest predictors of roadside PM2.5 in this setup. Taken together, the results support a practical way of pairing the two modelling philosophies: keep the physical dispersion model as the primary predictive engine, and use machine learning mainly for bias correction, gap-filling and short-term forecasting rather than as a full replacement. We close with some thoughts on what it would take to extend this framework — real monitoring data, multi-pollutant chemistry, street-canyon-resolving CFD — into something usable for actual urban air-quality decisions.

***Index Terms*—Air pollution modelling; Gaussian dispersion; Urban PM2.5; Machine learning; Random Forest; model validation; Hybrid simulation; Traffic emissions**

I. INTRODUCTION

Air pollution in urban areas results from a complex interaction between emission sources, atmospheric transport and dispersion processes, meteorology, and topography. Among the criteria pollutants, fine particulate matter (PM2.5) is of particular concern due to its ability to penetrate deeply into the respiratory tract and its established associations with cardiovascular and respiratory morbidity and mortality. In most rapidly urbanizing regions, road traffic is the dominant near-source contributor to ambient PM2.5 in city centers and along arterial corridors, compounded by industrial emissions, construction dust, biomass burning and secondary aerosol formation at the regional scale.

Air pollution simulation modelling provides civil and environmental engineers with a quantitative tool to translate emission inventories and meteorological conditions into predicted ambient concentrations, without the cost and lag associated with dense monitoring networks. Such models support source apportionment, health-impact assessment, urban and transport planning, early-warning systems, and evaluation of control strategies (e.g., low-emission zones, fleet electrification, traffic management) before they are implemented. Broadly, two modelling philosophies have matured over the past four decades: (i) physically based deterministic models, rooted in the advection–diffusion equation and typified by Gaussian plume/puff models, Eulerian grid models and computational fluid dynamics (CFD); and (ii) data-driven statistical and machine-learning (ML) models that learn empirical relationships between meteorological/traffic covariates and observed pollutant concentrations without explicitly solving the transport equations.

Each philosophy has complementary strengths. Physical models are interpretable, extrapolate more safely to new emission scenarios, and are consistent with the underlying physics of turbulent dispersion; however, they can be sensitive to parameterization errors, and their accuracy in complex urban geometries (street canyons, building wakes) is limited unless

computationally expensive CFD is used. ML models can achieve strong short-term predictive accuracy where dense historical data exist, and they naturally absorb unmodelled local effects, but they are data-hungry, can behave unpredictably outside their training envelope, and offer limited mechanistic insight. This has motivated growing interest in hybrid frameworks that use ML to correct or downscale the residual bias of a physical model rather than replace it outright — an approach sometimes termed model-output-statistics (MOS) in the atmospheric-science literature.

This paper develops and demonstrates such a hybrid simulation framework for urban roadside PM2.5. Because the purpose of the paper is methodological - to demonstrate the modelling, validation and comparison workflow in full — a representative synthetic case study is used, built from diurnal traffic and meteorological patterns and emission factors consistent with published urban corridor studies, rather than a specific city's proprietary monitoring dataset. The same workflow, code structure and validation protocol are directly transferable to any urban corridor once real traffic-count, meteorological and monitoring data are substituted for the illustrative inputs used here.

1.1 Research Problem Statement

i. Monitoring networks are sparse. Most cities operate only a handful of continuous ambient air-quality stations — nowhere near enough to resolve the sharp spatial gradients of traffic-related PM2.5 near busy corridors, intersections and street canyons.

ii. There is a persistent trade-off in model choice. Purely physical dispersion models are transparent and physically consistent, but carry systematic bias when local emission factors, stability classification or urban morphology are imperfectly known. Purely statistical/ML models can fit historical data well, yet generalise poorly the moment traffic, meteorological or emission-control conditions move outside what the model has seen before.

iii. There is also a validation gap in the literature. Many urban air-quality studies report a single model’s fit statistics in isolation, without a like-for-like comparison against an alternative modelling philosophy — which makes it hard for a practitioner to pick the right tool for a given planning question. Regulatory screening and short-term public-health forecasting are quite different jobs, and they don’t necessarily call for the same model.

1.2. Research Objectives

i. To develop a hybrid air pollution prediction framework.

ii To simulate and predict hourly roadside $PM_{2.5}$ concentrations.

iii To evaluate and compare the performance.

iv To identify the key factors influencing roadside $PM_{2.5}$ concentrations and assess the applicability of the hybrid modelling framework.

in the methodology and results that follow.

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II. METHODOLOGY

2.1 Overall Framework

The modelling framework comprises four stages, illustrated conceptually in Figure 1's underlying workflow: (i) construction of an hourly emission and meteorological input dataset for a representative urban arterial corridor; (ii) simulation of the corresponding roadside PM2.5 concentration field using a Gaussian line-source dispersion model, treated as the physically based 'first-guess' prediction; (iii) generation of a pseudo-observed concentration series by adding representativeness/instrument-type noise to the physical simulation, used here in place of a monitored dataset to demonstrate the full validation workflow; and (iv) training and validation of a Random Forest regression model, and of a hybrid Gaussian-plus-RF-residual-correction model, against a held-out test partition of the pseudo-observed series.

2.2 Gaussian Line-Source Dispersion Model

Vehicular emissions along an urban arterial are represented as a continuous, finite line source of length L, oriented at bearing θ_{road}, with time-varying emission strength $q(t)$ (g m^{-1} s^{-1}) obtained from hourly traffic volume $N(t)$ (veh/h) and a composite fleet-average PM2.5 emission factor EF (g veh^{-1} km^{-1}):

$$q(t) = N(t) \times EF / 3600 / 1000 \quad (1)$$

The steady-state ground-level concentration increment at a receptor located at perpendicular distance x from an (effectively infinite relative to σy at short range) line source, following the standard Gaussian line-source formulation used in CALINE-type models, is:

$$C(x, t) = [2\, q(t) / (\sqrt{(2\pi)}\, \sigma z(t)\, u(t) \sin \varphi(t))] \times \exp[-H^2 / (2\, \sigma z(t)^2)] \quad (2)$$

where $u(t)$ is wind speed (m/s), $\varphi(t)$ is the angle between wind direction and the road axis, $\sigma z(t)$ is the vertical dispersion coefficient (m) determined from the Pasquill–Gifford atmospheric stability class prevailing at hour t, and H is the effective release height of traffic-generated PM2.5 (taken as 0.5 m). Stability class was assigned using a simplified day/night rule: convective/near-neutral daytime conditions (07:00–17:00) were assigned a larger σz (more effective vertical mixing), evening/early-morning transition hours an intermediate σz, and night-time hours (23:00–04:00) the smallest σz, representing shallow, stable boundary layers that trap traffic emissions near the surface.

A nocturnal dilution correction, $f_{dil} = \min(3.0, \max(0.7, 600/H_{mix}(t)))$, was applied to the line-source term to represent enhanced near-surface accumulation when the mixing height $H_{mix}(t)$ collapses at night, and an urban background term $B(t)$ — representing regional and secondary aerosol contributions with its own diurnal cycle — was added to obtain the total simulated concentration:

$$C_{total}(t) = C(x, t) \times f_{dil}(t) + B(t) \quad (3)$$

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Table 2. Model inputs and their representation in the thirty-day case-study simulation.

Model input / parameter	Representation in the simulation
Road geometry	Single line source, length 1000 m, receptor set back 30 m from kerb, release height 0.5 m
Traffic volume	Diurnal bimodal pattern (AM peak ≈ 09:00, PM peak ≈ 18:30) with ±6% stochastic variability, 720 hourly values (30 days)
Emission factor	Composite fleet-average PM2.5 factor of 0.045 g/veh-km (representative of a mixed petrol/diesel/CNG urban fleet)
Wind speed / direction	Diurnal sinusoidal pattern with random perturbation; wind–road incidence angle computed each hour
Atmospheric stability	Simplified Pasquill–Gifford day/night classification controlling vertical dispersion coefficient (σz)
Mixing height	Diurnal boundary-layer growth/collapse cycle (120–1150 m) used to scale nocturnal trapping of traffic plume
Urban background	Regional/secondary aerosol contribution with diurnal and slow (30-day) trend components
Temperature / relative humidity	Diurnal cycle with stochastic noise; used only as ML predictors, not in the physical dispersion term

2.3 Data-Driven (Random Forest) Model

A Random Forest regression ensemble (300 trees, maximum depth 10, minimum leaf size 3) was trained to predict hourly PM2.5 directly from seven covariates — traffic volume, wind speed, wind direction, temperature, relative humidity, mixing height and hour-of-day — without reference to the Gaussian dispersion equations. The dataset (n = 720 hourly records) was split 75:25 into training and test partitions using a fixed random seed to ensure reproducibility, and performance was evaluated only on the held-out 25% test partition, consistent with standard machine-learning validation practice.

2.4 Hybrid (Bias-Correction) Model

A second Random Forest (300 trees, maximum depth 6, minimum leaf size 5 — a shallower ensemble appropriate for modelling a lower-variance residual signal) was trained to predict the residual, $r(t) = C_obs(t) - \text{Gaussian}(t)$, from the same seven covariates. The hybrid prediction was formed by adding the predicted residual back onto the physical model's output, $\text{Hybrid}(t) = \text{Gaussian}(t) + \hat{r}(t)$, evaluated on the identical held-out test partition used for the standalone models, ensuring a fair, like-for-like three-way comparison.

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2.5 Validation Statistics

Model performance was quantified using six standard air-quality model evaluation statistics computed on the test partition: root-mean-square error (RMSE) and mean absolute error (MAE), which measure overall prediction error in the units of the pollutant; the coefficient of determination (R^2); mean bias error (MBE) and fractional bias (FB = 2·mean(pred-obs)/mean(pred+obs)), which measure systematic over- or under-prediction; and Willmott's index of agreement (IOA), a bounded (0–1) measure of overall model skill that is less sensitive to outliers than R^2 alone. These are the same statistics recommended in USEPA and WMO model-evaluation guidance for regulatory and research-grade air-quality models.

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Free Convection Effects on Stokes Problem for An Infinite Vertical Plate Using Finite Element Technique

Dr. T. Arun Kumar
Associate Professor of Mathematics Government Degree College for Sciences, Adilabad

***Abstract*—A finite element technique is implemented for the free convection effects on stokes problem for an infinite vertical plate. The numerical values for velocity and temperature under various physical situations are obtained and have been analyzed graphically. The numerical results are compared with analytical solution and established the validity of finite element technique (Ritz method).**

***Index Terms*—specific heat, Grash of number, velocity, kinematic Viscosity, Finite element method.**

I. INTRODUCTION

The flow of an incompressible viscous fluid past an impulsively started infinite horizontal plate, in its own plane was studied first by Stokes [10]. It is known as Stokes problem in the literature. Because of its practical importance, it has been extended to bodies of different shapes by a number of researchers. Amongst them are Illingworth [5, Stewartson [9], Hall [4] and Elliott [3]. Illingworth considered the flow of a compressible gas with variable viscosity near an impulsively started vertical plate and the problem was solved by the method of successive approximation. Stewartson studied the flow of a viscous incompressible fluid past an impulsively started semi-infinite horizontal plate. Hall considered the flow past an impulsively started semi-infinite horizontal plate by finite difference method of mixed explicit-implicit type, which is convergent and stable hence it is free from any restrictions on the mesh size.

However, in Hall's analysis, only unsteady velocity field was studied. Elliott generalized Illingworth's problem by assuming a time dependent velocity and temperature for the plate, but neglected the viscous dissipative heat. However, in the above paper, only mathematical results were derived and no physical situation was discussed. In fact in such type of problems, from the engineering point of view, the physical aspects are very important.

So in order to present the physical situation of the flow past an impulsively started infinite vertical plate, Soundalgekar[12] considered the problem for incompressible fluid with constant

properties. Soundalgekar[12] was the first to present an exact solution to the flow of a viscous fluid past an impulsively started infinite vertical plate in its own plane. In this paper, the effect of maintaining the plate at different uniform temperature T_w was studied. Now, in this type of flow we can consider two physical situations. (1) The temperature of the plate is the same as that of the fluid extended to infinity; (2) the plate temperature differs from the temperature of the fluid at infinity. The second case is more important from both the physical and practical point of view. If the difference between the plate temperature T_w' and that of the fluid at infinity T_∞' .viz. $T_w' - T_\infty'$ is appreciable, then free convection currents are induced in the vicinity of the plate. Here is an attempt to study such a physical situation using Finite Element Method and hence, it is presented here. This problem has a variety physical application, example, Filtration process, the drying of porous materials in textile industries, etc. However, in many applications in space technology, the plate temperature doesn't remain uniform but varies with time. How the flow field will be affected by such a physical phenomenon? In order to clear this, Soundalgekar and Patil studied the Stokes problem for an infinite plate, whose temperature varies linearly with time and given a conclusion that the velocity near the plate increases when the time t and the Grashof number G_r increases.

It is well known fact that, the transition from conduction to convection is only due to the leading-edge effect that has propagated to a certain point. The distance of this point from the leading edge is known as maximum penetration distance $X_{Pmax.}$ Also, X_P is a function of t_1 (time) and y_1 (coordinates normal to the plate). Stokes also studied the flow of a viscous fluid past an infinite horizontal plate oscillating in its own plane. It has been proposed to study the effects of oscillating vertical plate and free convection currents on the flow of a viscous fluid which is stationary and extending to infinity. As the leading-edge effects are important in such a problem, it is interesting to know the effects of plate oscillations and the free convection currents on the leading-edge effects. So Soundalgekar studied the free convection effects on the flow past an infinite vertical oscillating plate by taking into account the presence of free convection currents. This study has been found to be useful in the design of space ships.

Mathematical Formulation

Here x_1 - axis is taken along an infinite plate in the vertical direction and y_1- axis is taken normal to the plate. Initially, the temperature of the plate is the same as that of the fluid. At $t > 0$ the plate starts moving impulsively in its own plane with velocity U_{0B} and its temperature is instantaneously raised or lowered to T_p which is thereafter maintained constant.

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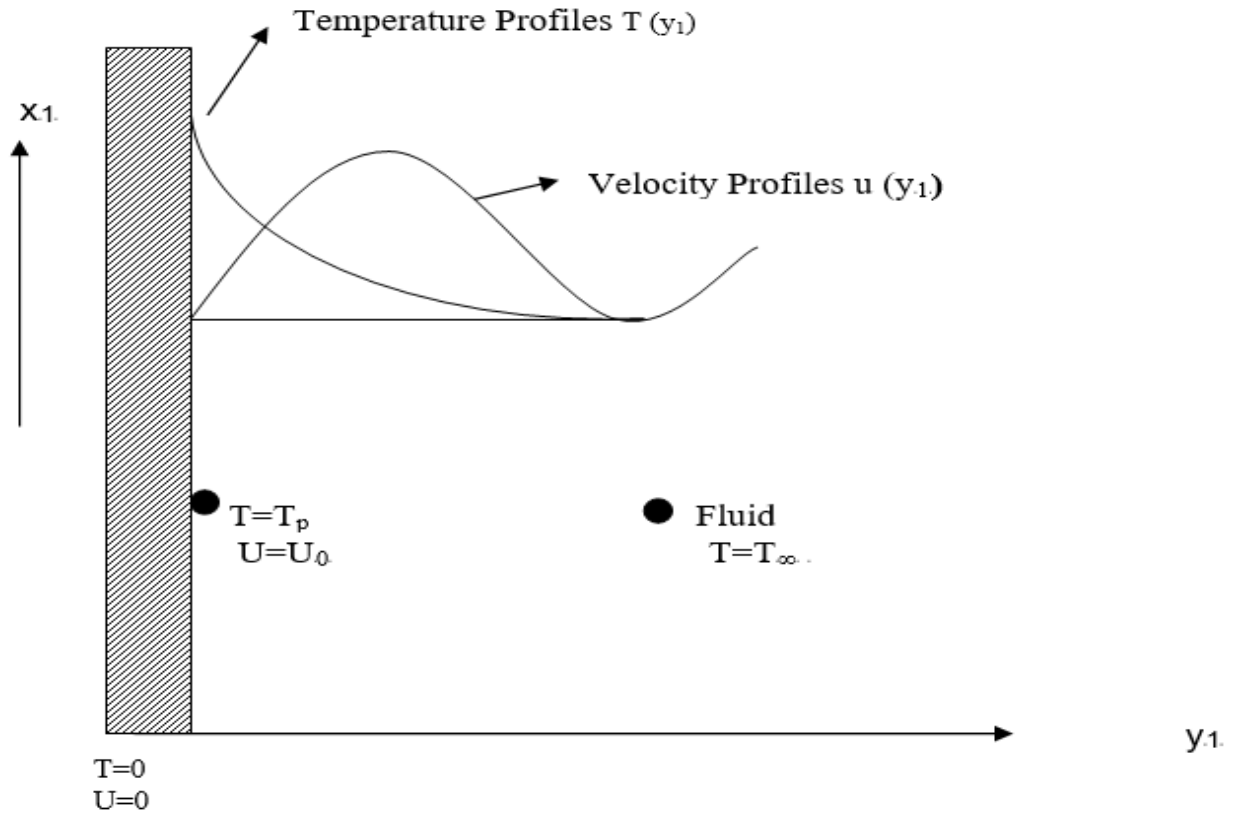


Fig 1: Geometry of the problem

As the plate is infinite, all variables in the problem are functions of y_1 and t_1 only. Therefore, the components of velocity are given by

$$v_{x_1} = u_1(y_1, t_1) \; ; \; v_{y_1} = 0 \quad \text{and} \quad v_{z_1} = 0. \tag{1}$$

All fluid properties are assumed constant except that the influence of the density variation with temperature is considered only in the body force term. Thus, the problem is governed by the following equations

$$\frac{\partial u_1}{\partial t_1} = g\beta(T_1 - T_\infty) + \nu \frac{\partial^2 u_1}{\partial y_1^2}, \tag{2}$$

$$\rho_1 c_p \frac{\partial T_1}{\partial t_1} = k \frac{\partial^2 T_1}{\partial y_1^2}. \tag{3}$$

Here, u_1 is the velocity of the fluid, T_1 the temperature of the fluid near the plate, T_∞ the temperature of the fluid far away from the plate, g the acceleration due to gravity, β the coefficient of volume expansion, ν the kinematic viscosity, ρ_1 the density of the fluid, k the thermal conductivity, c_p specific heat at constant pressure and t_1 is the time. In equation (3) the heat due to viscous dissipation is assumed to be negligible. This is possible when the velocity is small.

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The boundary conditions are

$$\left.\begin{aligned} &u_1(y_1, t_1) = U_0, \\ &T_1(y_1, t_1) = T_p \qquad \text{at } y_1 = 0; \\ &u_1(y_1, t_1) \to 0, \\ &T_1(y_1, t_1) \to T_\infty \qquad \text{as } y_1 \to \infty. \end{aligned}\right\} \tag{4}$$

On introducing the following non-dimensional quantities

$$\left.\begin{aligned} y &= \frac{y_1 U_0}{\nu}, \\ t &= \frac{t_1 U_0^2}{\nu}, \\ u &= \frac{u_1}{U_0}, \\ T &= \frac{T_1 - T_\infty}{T_p - T_\infty}, \\ P_r &= \frac{\mu c_p}{k} \ (\text{Prandtl number}), \\ G_r &= \frac{\nu g \beta (T_p - T_\infty)}{U_0^3} \ (\text{Grashof number}), \end{aligned}\right\} \tag{5}$$

in equations (2), (3) and (4) we have

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + G_r T, \tag{6}$$

$$\frac{\partial T}{\partial t} = \frac{1}{P_r} \frac{\partial^2 T}{\partial y^2}. \tag{7}$$

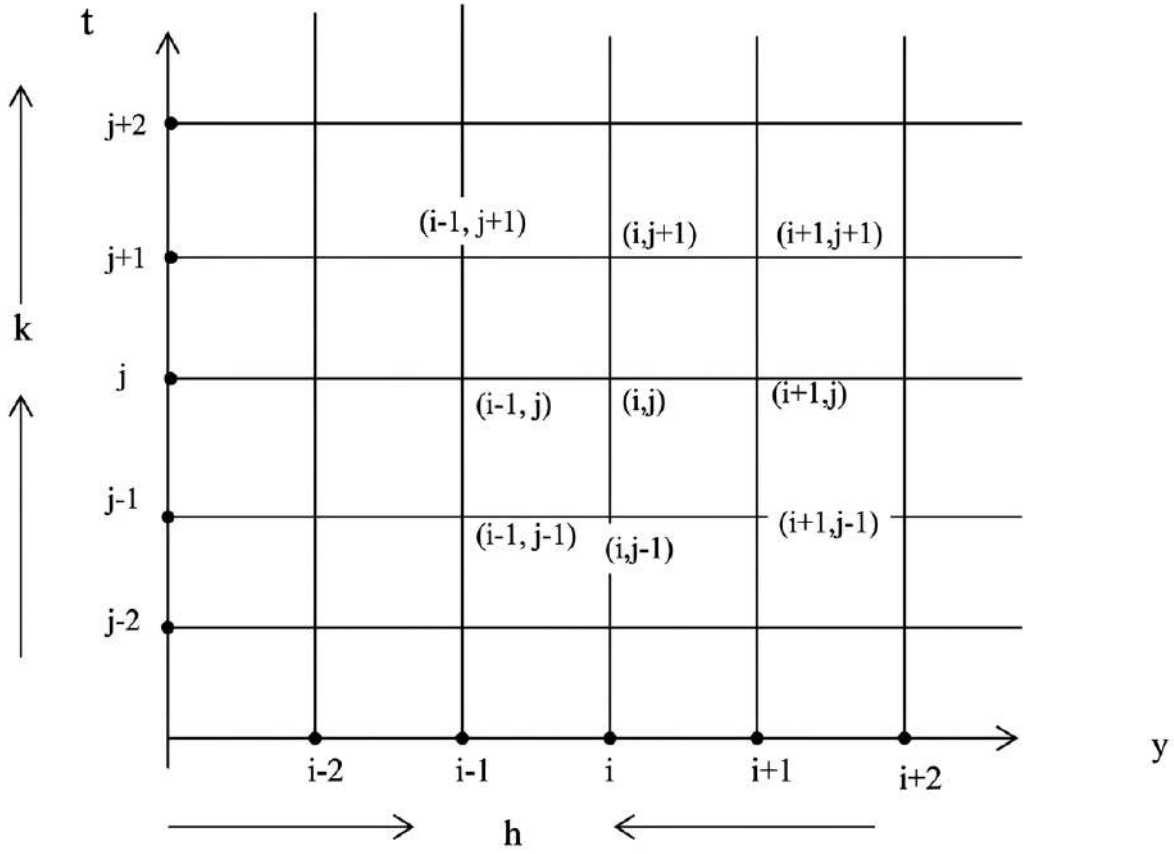
The corresponding initial and boundary conditions in non-dimensional quantities are

$$\left.\begin{aligned} &t < 0, \quad u(y, t) = 0, \quad T(y, t) = 0; \\ &t > 0, \quad u(0, t) = 1, \quad T(0, t) = 1; \\ &t > 0, \quad u(\infty, t) = 0, \quad T(\infty, t) = 0. \end{aligned}\right\} \tag{8}$$

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II. METHOD OF SOLUTION

The Finite Element Method (i.e., Ritz method) has been used to solve equations (6) and (7) subject to the boundary condition (8). To obtain the difference equations, the region is divided into a grid or mesh of lines parallel to y and t axis. Solution of the difference equations is obtained at the intersection of these mesh lines, called nodes. The values of the dependent variables u and T at the nodal points along the planes y=0 and t=0 are given by u (0, t), T (0, t), u (y, 0) and T(y, 0) thus are known from the initial and boundary conditions. In the Figure (2) h, k are the mesh sizes along y and t directions respectively. A scheme is required to find single value at next time level in terms of known values from present time level. We use finite element method and apply trapezoidal rule to get the Crank-Nicolson method.



Now, we consider equation (7)

$$\frac{\partial T}{\partial t} = \frac{1}{P_r} \frac{\partial^2 T}{\partial y^2}.$$

Using finite element method with crank-nicolson discretization taking h=0.05, k=0.0025 therefore $r=k / h^2 =1$.

The element equation for the typical element (e) $y_j \le y \le y_k$ for the boundary value problem may be written as

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$$j^e = 1/2 \int_{yj}^{yk} \left[\left(\frac{\partial T^e}{\partial y} \right)^2 + 2T^e p_r \frac{\partial T^e}{\partial t} \right] dy$$

For the linear piecewise approximate solution

$$T^e = N_J(y)T_j(t) + N_k(y)T_k(t)$$

The element equation is given by

$$j^e = 1/2 \int_{y_j}^{y_k} \left\{ \left([N_j^{'} \quad N_k^{'}] \begin{bmatrix} T_J \\ T_k \end{bmatrix} \right)^2 + 2P_r [N_J \quad N_K] \begin{bmatrix} T_J \\ T_k \end{bmatrix} [N_j \quad N_K] \begin{bmatrix} \dot{T}_j \\ \dot{T}_k \end{bmatrix} \right\} dy$$

$$\frac{\partial j^e}{\partial T_j} = 1/2 \int_{y_j}^{y_k} \left\{ 2 \left([N_j^{'} \quad N_k^{'}] \begin{bmatrix} T_j \\ T_k \end{bmatrix} \right) N_j^{'} + 2P_r N_j [N_j \quad N_k] \begin{bmatrix} \dot{T}_j \\ \dot{T}_k \end{bmatrix} \right\} dy$$

$$\frac{\partial j^e}{\partial T_j} = \int_{y_j}^{y_k} \left\{ \left([N_j^{'} \quad N_k^{'}] \begin{bmatrix} T_j \\ T_k \end{bmatrix} \right) N_j^{'} + P_r N_j [N_j \quad N_k] \begin{bmatrix} \dot{T}_j \\ \dot{T}_k \end{bmatrix} \right\} dy$$

$$\frac{\partial j^e}{\partial T_k} = \frac{1}{2} \int_{y_j}^{y_k} \left\{ 2 \left([N_j^{'} \quad N_k^{'}] \begin{bmatrix} T_j \\ T_k \end{bmatrix} \right) N_k^{'} + 2P_r N_k [N_j \quad N_k] \begin{bmatrix} \dot{T}_j \\ \dot{T}_k \end{bmatrix} \right\} dy$$

$$\frac{\partial j^e}{\partial T_k} = \int_{y_j}^{y_k} \left\{ \left([N_j^{'} \quad N_k^{'}] \begin{bmatrix} T_j \\ T_k \end{bmatrix} \right) N_k^{'} + P_r N_k [N_j \quad N_k] \begin{bmatrix} \dot{T}_j \\ \dot{T}_k \end{bmatrix} \right\} dy$$

$$\frac{\partial j^e}{\partial \phi^e} = \int_{y_j}^{y_k} \left\{ \begin{pmatrix} N_j^{'}[N_j^{'} & N_k^{'}] \\ N_k^{'}[N_j^{'} & N_k^{'}] \end{pmatrix} \begin{bmatrix} T_j \\ T_k \end{bmatrix} + P_r \begin{pmatrix} N_j[N_j & N_k] \\ N_k[N_j & N_k] \end{pmatrix} \begin{bmatrix} \dot{T}_j \\ \dot{T}_k \end{bmatrix} \right\} dy$$

$$\frac{\partial j^e}{\partial \phi^e} = \int_{y_j}^{y_k} \left\{ \begin{pmatrix} [N_j^{'} N_j^{'} & N_j^{'} N_k^{'}] \\ [N_k^{'} N_j^{'} & N_k^{'} N_k^{'}] \end{pmatrix} \begin{bmatrix} T_j \\ T_k \end{bmatrix} + P_r \begin{pmatrix} [N_j N_j & N_j N_k] \\ [N_k N_j & N_k N_k] \end{pmatrix} \begin{bmatrix} \dot{T}_j \\ \dot{T}_k \end{bmatrix} \right\} dy$$

Where prime denotes differentiation w.r.t. to 'y' and dot represent differentiation w.r.t. to 't'

$$\text{Here } N_j^{'} = \frac{-1}{h} \quad ; N_k^{'} = \frac{1}{h}; \quad \text{where } h = y_k - y_j;$$

Simplifying, we get

$$\frac{1}{h} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} T_J \\ T_K \end{bmatrix} + \frac{h}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} \dot{T}_J \\ \dot{T}_K \end{bmatrix} = 0$$

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The condition for the extremization of the functional j^e w.r.t the nodal values T_j and T_k are given by

$$\frac{\partial j^e}{\partial \phi^e}=\sum_{e=1}^{n+1} \frac{\partial j^e}{\partial \phi^e}=0$$

In order to get the differential equation at the knot y_i we write the element equations for the elements

$$y_{i-4} \le y \le y_{i-3};\ y_{i-3} \le y \le y_{i-2};\ y_{i-2} \le y \le y_{i-1};\ y_{i-1} \le y \le y_i;$$
$$y_i \le y \le y_{i+1};\ y_{i+1} \le y \le y_{i+2};\ y_{i+2} \le y \le y_{i+3}; y_{i+3} \le y \le y_{i+4};$$

For the elements $y_{i-4} \le y \le y_{i-3}$ and $y_{i-3} \le y \le y_{i-2}$

the assembled equation is given as

$$\frac{1}{6}\begin{bmatrix} 2 & 1 & 0 \\ 1 & 2+2 & 1 \\ 0 & 1 & 2 \end{bmatrix}\begin{bmatrix} \dot{T}_{i-4} \\ \dot{T}_{i-3} \\ \dot{T}_{i-2} \end{bmatrix}+\frac{1}{p_r h^2}\begin{bmatrix} 1 & -1 & 0 \\ -1 & 1+1 & -1 \\ -1 & 1 & 0 \end{bmatrix}\begin{bmatrix} T_{i-4} \\ T_{i-3} \\ T_{i-2} \end{bmatrix}=0$$

Thus, assembling all the elements we get

$$\begin{bmatrix} 2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 4 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 4 \end{bmatrix}\begin{bmatrix} \dot{T}_{i-4} \\ \dot{T}_{i-3} \\ \dot{T}_{i-2} \\ \dot{T}_{i-1} \\ \dot{T}_i \\ \dot{T}_{i+1} \\ \dot{T}_{i+2} \\ \dot{T}_{i+3} \\ \dot{T}_{i+4} \end{bmatrix}+$$

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$$\frac{1}{p_r h^2}\begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 2 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 2 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 2 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 2 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 2 \end{bmatrix}\begin{bmatrix} T_{i-4} \\ T_{i-3} \\ T_{i-2} \\ T_{i-1} \\ T_i \\ T_{i+1} \\ T_{i+2} \\ T_{i+3} \\ T_{i+4} \end{bmatrix}=0$$

We put the row corresponding to the knot 'i' to zero and write the semi discretization as

$$\frac{1}{6}\left(\dot{T}_{i-1}+4\dot{T}_i+\dot{T}_{i+1}\right)=\left(\frac{1}{p_r h^2}\right)\left(T_{i-1}-2T_i+T_{i+1}\right)$$

Applying the trapezoidal rule we obtain the crank-nicolson method

$$\frac{1}{6k}\left[\left(T_{i-1}^{n+1}-T_{i-1}^{n}\right)+4\left(T_i^{n+1}-T_i^{n}\right)+\left(T_{i+1}^{n+1}-T_{i+1}^{n}\right)\right]=$$

$$\frac{1}{p_r h^2}\left[\frac{\left(T_{i-1}^{n+1}+T_{i-1}^{n}\right)}{2}-2\frac{\left(T_i^{n+1}+T_i^{n}\right)}{2}+\frac{\left(T_{i+1}^{n+1}+T_{i+1}^{n}\right)}{2}\right]$$

$$\left[\left(T_{i-1}^{n+1}-T_{i-1}^{n}\right)+4\left(T_i^{n+1}-T_i^{n}\right)+\left(T_{i+1}^{n+1}-T_{i+1}^{n}\right)\right]=$$

$$\frac{3r}{p_r}\left[\frac{\left(T_{i-1}^{n+1}+T_{i-1}^{n}\right)}{2}-2\frac{\left(T_i^{n+1}+T_i^{n}\right)}{2}+\frac{\left(T_{i+1}^{n+1}+T_{i+1}^{n}\right)}{2}\right]$$

Simplifying above equation we get

$$\left(1-\frac{3r}{p_r}\right)T_{i-1}^{n+1}+\left(4+\frac{6r}{p_r}\right)T_i^{n+1}+\left(1-\frac{3r}{p_r}\right)T_{i+1}^{n+1}=$$

$$\left(1+\frac{3r}{p_r}\right)T_{i-1}^{n}+\left(4-\frac{6r}{p_r}\right)T_{i-1}^{n}+\left(1+\frac{3r}{p_r}\right)T_{i-1}^{n}$$

For h=0.05, k=0.0025 and r =1 the nodal points (y_n, t_n) are shown in the figure (2), where i =1(1)9 and n=1, 2, 3….

We solve the system of above equations using Gauss –Seidel method.

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t	Y	Analytical Solution	Numerical Solution	Percentage of Error
0.0075	0	1	1	0.0000
0.0075	0.05	0.7261	0.6799	0.0005
0.0075	0.1	0.4846	0.4664	0.0002
0.0075	0.15	0.2944	0.2502	0.0004
0.0075	0.2	0.1621	0.1144	0.0005
0.0075	0.25	0.0805	0.0472	0.0003
0.0075	0.3	0.0360	0.0182	0.0002
0.0075	0.35	0.0144	0.0067	0.0001
0.0075	0.4	0.0052	0.0023	0.0000
0.0075	0.45	0.0017	0.0008	0.0000
0.0075	0.5	0.0005	0.0003	0.0000
0.0075	0.55	0.0001	0.0001	0.0000
0.0075	0.6	0.0000	0.0000	0.0000
0.0075	0.65	0.0000	0.0000	0.0000
0.0075	0.7	0.0000	0.0000	0.0000
0.0075	0.75	0.0000	0.0000	0.0000
0.0075	0.8	0.0000	0.0000	0.0000
0.0075	0.85	0.0000	0.0000	0.0000
0.0075	0.9	0.0000	0.0000	0.0000
0.0075	0.95	0.0000	0.0000	0.0000
0.0075	1	0.0000	0.0000	0.0000

Table 1: Comparison of temperature profiles when P_r=0.7333

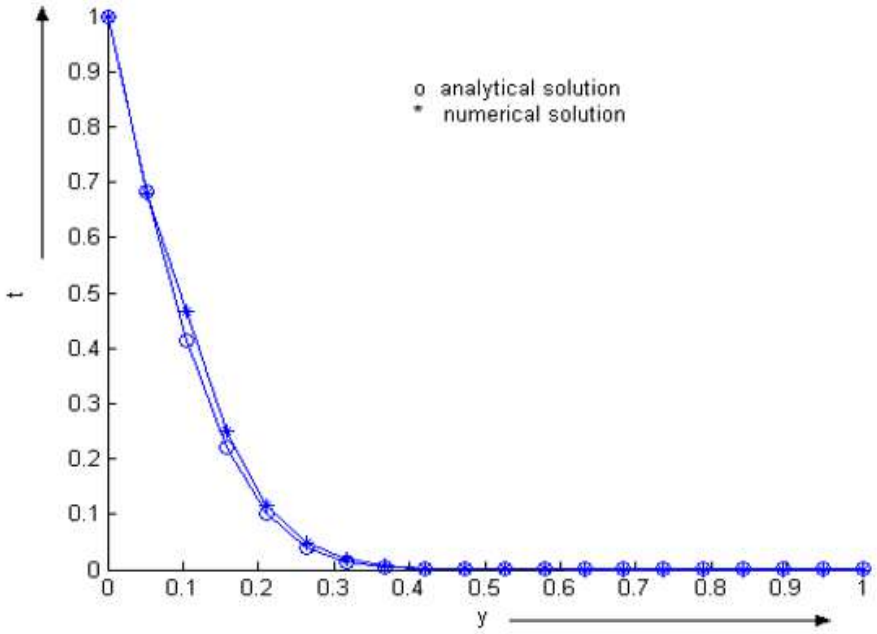


Fig 3: Comparison of temperature Profiles when P_r=0.7333

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Discussion:

Comparisons of Numerical Solutions of temperature with analytical solutions (annexure 2) are plotted in figure (3) here the accuracy is very high between the numerical solutions and analytical solutions. Therefore we can say that Finite Element Method is Valid.

Now, we consider equation (6)

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + G_r T$$

Using finite element method with crank nicolson- discretization taking h=0.05 and r=1

The element equation for the typical element (e) $y_j \le y \le y_k$ for the boundary value problem may be written as

$$j^e = 1/2 \int_{yj}^{yk} \left[\left(\frac{\partial U^e}{\partial y} \right)^2 + 2U^e \frac{\partial U^e}{\partial t} - 2U^e G_r T \right] dy$$

For the linear piecewise approximate solution

$$U^e = N_J(y) U_j(t) + N_k(y) U_k(t)$$

The element equation is given by

$$j^e = 1/2 \int_{y_j}^{y_k} \left\{ \left([N_j' \quad N_k'] \begin{bmatrix} U_j \\ U_k \end{bmatrix} \right)^2 + 2[N_j \quad N_k] \begin{bmatrix} U_J \\ U_K \end{bmatrix} [N_j \quad N_k] \begin{bmatrix} \dot{U}_J \\ \dot{U}_K \end{bmatrix} - 2[N_J \quad N_K] \begin{bmatrix} U_j \\ U_k \end{bmatrix} G_r T \right\} dy$$

Simplifying above equation we get

$$(1\text{-}3r) U_{i-1}^{n+1} + (4+6r)\ U_i^{n+1} + (1\text{-}3r)\ U_{i+1}^{n+1} =$$

$$(1+3r) U_{i-1}^{n} + (4\text{-}6r)\ U_{i-1}^{n} + (1+3r)\ U_{i-1}^{n} + 6\, G_r T_i^n \text{ k}$$

For h=0.05 and r =1 the nodal points (y_n, t_n) are shown in the figure (2.2)

Where i =1(1)9 and n=1, 2, 3….

We solve the system of above equations using Gauss –Seidel method.

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t	y	Analytical Solution	Numerical Solution	Percentage of Error |
0.0075	0	1	1	0.0000
0.0075	0.05	0.726713	0.6421	0.0008
0.0075	0.1	0.48455	0.3924	0.0009
0.0075	0.15	0.294406	0.1706	0.0012
0.0075	0.2	0.162111	0.0615	0.0010
0.0075	0.25	0.080549	0.0197	0.0006
0.0075	0.3	0.035993	0.0059	0.0003
0.0075	0.35	0.014425	0.0017	0.0001
0.0075	0.4	0.005174	0.0005	0.0000
0.0075	0.45	0.001658	0.0001	0.0000
0.0075	0.5	0.000474	0.0000	0.0000
0.0075	0.55	0.000121	0.0000	0.0000
0.0075	0.6	2.74E-05	0.0000	0.0000
0.0075	0.65	5.53E-06	0.0000	0.0000
0.0075	0.7	9.93E-07	0.0000	0.0000
0.0075	0.75	1.58E-07	0.0000	0.0000
0.0075	0.8	2.24E-08	0.0000	0.0000
0.0075	0.85	2.82E-09	0.0000	0.0000
0.0075	0.9	3.15E-10	0.0000	0.0000
0.0075	0.95	3.13E-11	0.0000	0.0000
0.0075	1	2.75E-12	0.0000	0.0000

Table 2: Comparison of Velocity when P_r=6.75

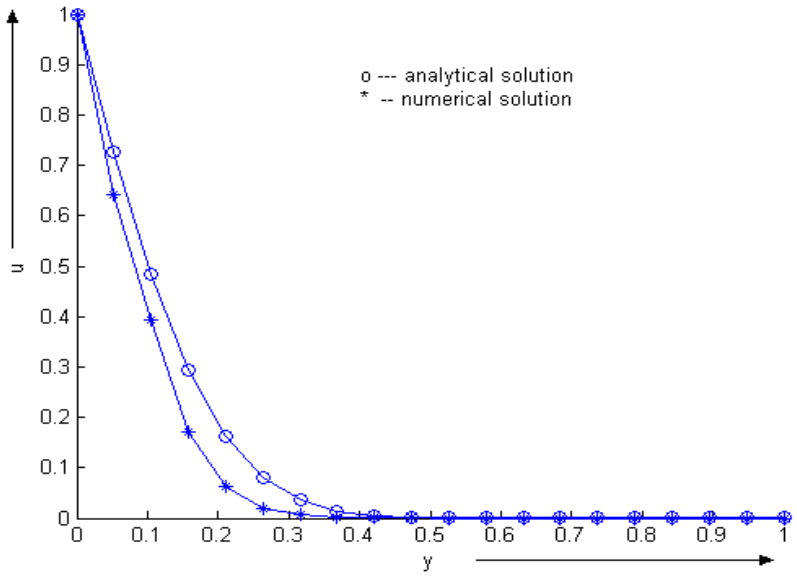


Fig 4: Comparison of Velocity when P_r=6.75

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Discussion

Comparison of numerical solutions of velocity with the corresponding analytical solutions (annexure 4) are plotted in Figure (4). From the figure, it is observed that the error estimation between numerical and analytical values are almost negligible. Thus establishing the validity of the method.

y	GB_{rB} =5 , t=3K	GB_{rB} =5 , t=6K	GB_{rB} =10 , t=3K
0	1.0000	1.0000	1.0000
0.05	0.6480	0.7799	0.6556
0.1	0.4005	0.5617	0.4091
0.15	0.1768	0.3855	0.1829
0.2	0.0648	0.2392	0.0681
0.25	0.0213	0.1387	0.0228
0.3	0.0065	0.0737	0.0071
0.35	0.0019	0.0356	0.0021
0.4	0.0005	0.0157	0.0006
0.45	0.0001	0.0065	0.0002
0.5	0.0000	0.0025	0.0001
0.55	0.0000	0.0009	0.0000
0.6	0.0000	0.0003	0.0000
0.65	0.0000	0.0001	0.0000
0.7	0.0000	0.0000	0.0000
0.75	0.0000	0.0000	0.0000
0.8	0.0000	0.0000	0.0000
0.85	0.0000	0.0000	0.0000
0.9	0.0000	0.0000	0.0000
0.95	0.0000	0.0000	0.0000
1	0.0000	0.0000	0.0000

Table 3: Numerical values of Velocity when GB_{rB} =5, GB_{rB}=10 and t=3k, t=6k

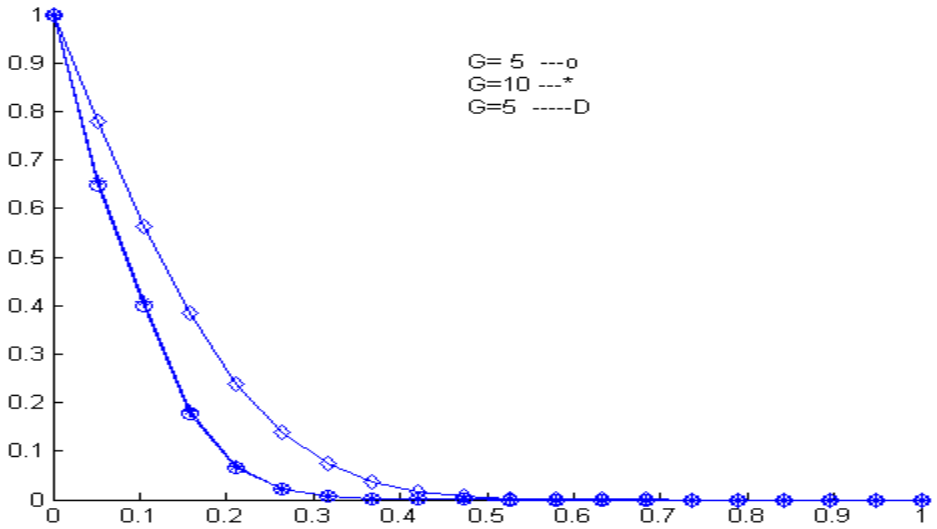


Fig 5: Velocity profiles when GB_{rB} =5, $GB_{r\,B}$=10 and t=3k, t=6k

y	GB_r=-5 , t=3K	GB_r=-5, t=6K	GB_r=-10 , t=3K
0	1.0000	1.0000	1.0000
0.05	0.6330	0.7537	0.6254
0.1	0.3832	0.5272	0.3745
0.15	0.1646	0.3522	0.1585
0.2	0.0582	0.2125	0.0549
0.25	0.0183	0.1197	0.0167
0.3	0.0053	0.0614	0.0046
0.35	0.0014	0.0283	0.0012
0.4	0.0004	0.0118	0.0003
0.45	0.0001	0.0045	0.0001
0.5	0.0000	0.0016	0.0000
0.55	0.0000	0.0005	0.0000
0.6	0.0000	0.0002	0.0000
0.65	0.0000	0.0000	0.0000
0.7	0.0000	0.0000	0.0000
0.75	0.0000	0.0000	0.0000
0.8	0.0000	0.0000	0.0000
0.85	0.0000	0.0000	0.0000
0.9	0.0000	0.0000	0.0000
0.95	0.0000	0.0000	0.0000
1	0.0000	0.0000	0.0000

Table 4: Numerical values of velocity when GB_{rB} =-5, GB_{rB} =-10 and t=3k, t=6k

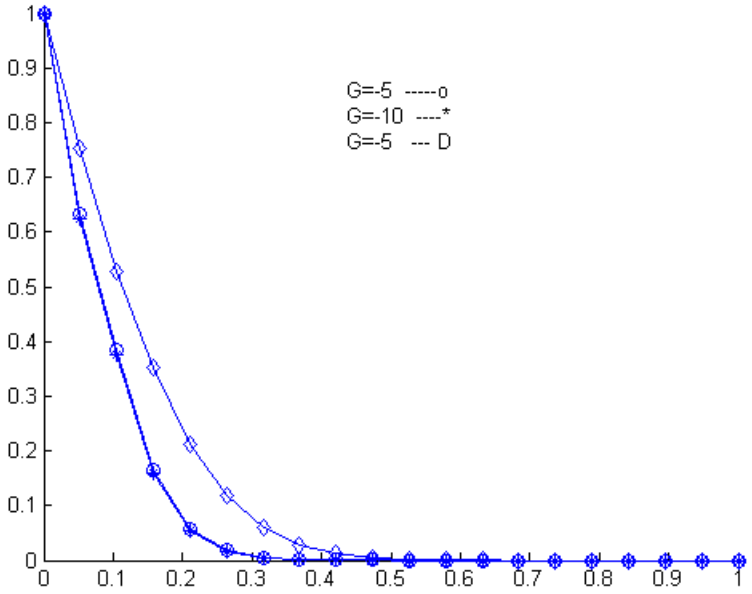


Fig 6: Velocity when GB_{rB} =-5, GB_{rB}=-10 and t=3k, t=6k

Discussion

The numerical values of velocity profiles for different values of G_r (Grashoff number) and time t have been tabulated under Table (3). From physical point of view $G_r > 0$ corresponds to externally cooled plate. Hence, for an externally cooled plate, we can observe that, as G_r increases, velocity also increase by keeping t fixed which can be seen from figure (5). Also from this figure, it can be observed that as t increases for G_r fixed, the velocity increases. Further, physically $G_r < 0$ corresponds to an externally heated plate as free convection currents are carried towards the plate. For different values of GB_{rB} , when time 't' is fixed velocities are computed and presented in table (4) and plotted and shown in figure (6). Further, it is observed that as GB_{rB} decreases from -5 to-10, the velocity decreases.

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Shadow Tag Design and Implementation of A 2d Survival Arcade Game with A Delayed Mimicry Ai

[1]Dr.Lalji Prasad, [2]Karan Sharma
[1]*Supervised by, HOI, IAC, Department of Advance Computing Specialization, SAGE University, Indore*
[2]*Submitted by, Department of Advance Computing Specialization, SAGE University, Indore*

***Abstract*—Artificial Intelligence (AI) is increasingly applied within digital game development to build intelligent mechanics that boost player engagement, adaptability, and strategic thinking. Standard 2D arcade games typically rely on scripted enemy behavior and fixed movement routines, which makes gameplay predictable and limits replay value. This paper presents Shadow Tag, an AI-driven 2D survival arcade game built around a Delayed Mimicry AI, in which the antagonist replays the player's own past movement trajectory after a set time delay. Rather than relying on conventional pursuit logic such as pathfinding or direct target tracking, the proposed AI turns the player's earlier actions into an evolving obstacle, demanding ongoing strategic planning and spatial awareness.**

The game is built with Python and the Pygame framework using an object-oriented design that combines player control, a delayed shadow AI, procedurally generated obstacles, collectible objects, collision detection, animation handling, particle effects, persistent score tracking, and a state-driven interface. The delayed mimicry effect is produced by recording the player's position each frame and replaying those coordinates after a set delay, yielding an opponent whose behavior continually shifts in response to what the player has done. Supporting systems such as procedural level generation, real-time collision handling, high-score saving, and consistent 60 FPS execution round out an immersive, responsive play experience.

The working implementation shows that the proposed framework successfully blends intelligent AI behavior with real-time mechanics while keeping performance stable and gameplay interactive. The delayed mimicry model raises gameplay difficulty without demanding computationally heavy machine learning, giving an efficient and scalable AI approach for arcade-style titles. The architecture leaves room for future additions such as adaptive difficulty, reinforcement-learning-driven enemy behavior, multiplayer support, procedural level design, and more advanced AI decision-making. Shadow Tag thus offers a fresh way to bring behavior-driven artificial intelligence into modern 2D survival games

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while showing how AI concepts can be put to practical use in interactive entertainment and game development.

***Index Terms*—Artificial Intelligence, Delayed Mimicry AI, 2D Survival Arcade Game, Shadow Tag, Python, Pygame, Game Development, Player Behavior Modelling, Real-Time Game Systems, Collision Detection, Procedural Generation, Interactive Entertainment.**

I. INTRODUCTION

1.1 Background and Motivation

Traditional 2D survival and arcade titles typically give enemies fixed paths, random movement routines, or basic pathfinding that simply chases the player's current location [11, 13]. These techniques are cheap to compute, but they tend to grow predictable with repeated play, which hurts engagement and long-term replay value.

Advances in Artificial Intelligence have made it possible to build game agents that respond dynamically to how a player behaves [2, 10]. AI-based gameplay mechanics deepen immersion by giving players opponents that change along with their choices. Yet many advanced AI approaches — reinforcement learning, deep neural networks, evolutionary algorithms — need heavy computation and elaborate training pipelines [3, 4], which makes them hard to fit into lightweight arcade games.

Shadow Tag was motivated by the goal of raising gameplay difficulty through an original AI mechanism that avoids expensive machine learning models. Rather than learning from training data, the Delayed Mimicry AI keeps a running record of the player's movement and plays it back after a fixed delay. As a result, every move the player makes shapes what happens later in the game, pushing players to think ahead about the consequences of their own actions.

The project also sets out to show that inventive AI design can meaningfully improve player experience even with fairly simple algorithms and data structures. By bringing together delayed movement replay, procedurally placed obstacles, collision detection, animation, and persistent scoring, Shadow Tag serves as a working example of how AI ideas can be woven into modern game development.

1.2 Problem Statement

Most 2D arcade survival games depend on familiar enemy behaviors — direct chasing, random wandering, or fixed movement routes [11]. These are simple to build, but they tend to yield repetitive gameplay with little strategic depth. Once players learn how the enemy behaves, the challenge fades, which lowers engagement and replay ability over time.

Building adaptive AI that produces unpredictable, intelligent gameplay usually calls for advanced machine learning methods requiring sizeable datasets, long training runs, and considerable computing power [3, 4]. These demands are frequently unrealistic for small, independently developed games built in Python and Pygame.

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The core challenge tackled in this research is designing and building an AI opponent that is both intelligent and computationally light — one that keeps adapting to the player without relying on complex learning algorithms. The project examines whether replaying delayed movement can produce a genuinely challenging environment while still keeping real-time performance, straightforward implementation, and room to grow.

1.3 Research Objectives

The primary objectives of this research are:

1. Design and build a 2D survival arcade game in Python with the Pygame framework that offers an engaging, strategically demanding gameplay experience.
2. Implement a Delayed Mimicry AI that plays back the player's own movement history after a fixed time delay, forming an adaptive AI opponent.
3. Build a real-time game architecture using object-oriented programming, event handling, animation, collision detection, procedural object placement, and game-state management.
4. Implement an efficient system for recording and replaying movement that reproduces player motion accurately while keeping the frame rate steady.
5. Assess how effectively behavior-driven AI boosts player engagement, strategic thinking, and replayability relative to conventional enemy movement schemes.
6. Lay a scalable groundwork that supports later additions such as reinforcement learning, adaptive difficulty, procedural level generation, multiplayer play, and smarter path planning.

1.4 Scope and Original Contributions

This research covers the design, build, and evaluation of an AI-driven 2D survival arcade game centered on a novel delayed-mimicry mechanic. Its scope spans game architecture, AI behavior modelling, procedural environment generation, collision detection, animation, score persistence, and interface design, all implemented in Python and Pygame. The project's central focus is lightweight AI approaches that deliver intelligent gameplay without needing machine learning training or dedicated hardware.

The original contributions of this research include:

1. A new Delayed Mimicry AI design where the enemy plays back the player's own movement history rather than depending on fixed patterns or classic pathfinding [11, 13].
2. A lightweight, behavior-driven AI framework that produces adaptive, strategic gameplay without neural networks, reinforcement learning, or costly training [3, 4].
3. A real-time system for recording, storing, and replaying player positions with precise timing while keeping gameplay smooth.
4. A unified object-oriented architecture bringing together player control, delayed AI behavior, procedural obstacle generation, collision detection, animation, particle effects, persistent scoring, and a state-driven UI [28, 29].

5. A scalable framework open to future extension with more advanced AI methods — reinforcement learning, adaptive enemy behavior, procedural level generation, multiplayer play, and richer game analytics.

II. LITERATURE REVIEW

This section surveys existing work on Artificial Intelligence (AI), game development, behavior-driven enemy systems, procedural content generation, and real-time game architectures. It weighs the strengths and shortcomings of current approaches and points to the research gap that the proposed Shadow Tag system addresses.

2.1 Artificial Intelligence in 2D Game Development

Artificial Intelligence now plays a central role in modern games, enabling intelligent non-player characters (NPCs), adaptive gameplay, and believable interactions [2]. Traditional 2D games mostly lean on rule-based AI, finite state machines (FSM), and basic pathfinding to control enemies [11, 12]. These approaches are cheap to run and simple to build, but tend to become predictable with repeated play. Recent work suggests behavior-driven AI can raise engagement by making opponents feel more dynamic and responsive [10]. Even so, many AI implementations favor chasing or attacking over building gameplay mechanics that truly stem from player actions — pointing to a need for AI models that stay lightweight while still delivering a real challenge.

2.2 Behavior Modelling and Enemy Movement Algorithms

The difficulty and replay value of arcade games hinge heavily on enemy behavior. Common approaches include A* pathfinding, Breadth-First Search (BFS), waypoint navigation, and random movement [11, 13]. More sophisticated techniques — behavior trees, utility-based AI, reinforcement learning — let enemies adapt intelligently as conditions change [4, 10]. These add realism but come with heavier computation and implementation cost. Little research has looked at enemy behavior generated directly from a player's own history of actions, which is exactly the gap the proposed Delayed Mimicry AI fills, having the opponent recreate the player's past movement instead of hunting for the player independently.

2.3 Python and Pygame for AI-Based Game Development

For educational and research-oriented game projects, Python is one of the most popular choices thanks to its readable syntax, rich library ecosystem, and object-oriented design [14, 16]. Pygame gives developers solid support for rendering, sprite handling, animation, collision detection, keyboard input, sound, and frame-based game loops [15, 17]. Many academic projects have shown Python and Pygame work well for AI-based 2D games and rapid prototyping, though most stick to basic mechanics rather than introducing AI behavior that meaningfully shapes player strategy.

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2.4 Procedural Content Generation and Real-Time Game Systems

Procedural Content Generation (PCG) has become a key way to keep games replayable, generating obstacles, collectibles, maps, and environment objects on the fly [8, 9]. Randomizing object placement cuts down on repetition and keeps players interested. Paired with a real-time loop running at a steady frame rate, procedural systems give a smooth, responsive experience. Prior work has focused mostly on procedural environments and given less attention to pairing that content with AI behavior that evolves alongside player movement. Shadow Tag brings both procedural obstacle generation and behavior-driven AI together in one architecture.

2.5 Delayed Mimicry and Player Behavior-Based AI

A number of commercial games have used shadow-style mechanics where past player actions shape later events — Sonic the Hedgehog's Mephiles, Aragami, Shadow Gambit: The Cursed Crew, and Prince of Persia all feature shadow-inspired enemies or time-based movement. These, however, generally rely on scripted design or preset AI rather than a genuine real-time replay of player movement. Very little existing literature covers delayed-mimicry algorithms that turn a player's movement history into an adaptive adversary. The proposed Delayed Mimicry AI fills this gap by continually recording player positions and replaying them after a fixed delay, producing an opponent shaped entirely by the player — an idea that echoes the Digital Twin concept of a continuously synchronized virtual counterpart [5, 6, 7].

2.6 Research Gap and Motivation

This review points to several gaps in current AI-based arcade systems. Most enemy AI still relies on pathfinding, scripted movement, or heavy machine learning [10, 11], each of which either grows predictable over time or demands processing power that doesn't suit lightweight Python/Pygame games. Little work has looked at AI that draws directly on a player's movement history to build enemy intelligence. Shadow Tag responds to this by offering a lightweight Delayed Mimicry AI that produces adaptive gameplay through movement replay, combining real-time recording, procedural environments, an object-oriented design, and efficient mechanics into a scalable, computationally light AI framework for 2D survival arcade games.

Research Gap Identification

The comparative analysis reveals several significant research gaps in existing AI-based game development approaches:

1. Predictable enemy behavior: most conventional AI relies on finite state machines, waypoint navigation, or pathfinding that eventually becomes predictable with repeated play [11, 12].
2. High computational cost: reinforcement learning and deep neural networks give adaptive behavior but require heavy training, strong hardware, and large datasets — impractical for lightweight arcade games [3, 4].
3. Limited player-centric AI: existing enemy AI mostly chases or attacks the player's current position rather than drawing on the player's own history to build intelligent behavior.

4. No delayed-mimicry mechanisms: very few studies examine AI that replays a player's past movement to create future gameplay challenges.
5. Weak integration of lightweight AI with procedural gameplay: research tends to treat procedural content and AI behavior as separate concerns, with little linkage between adaptive enemies and dynamically generated environments [8, 9].
6. Need for scalable, educational AI frameworks: there remains a need for computationally efficient AI designs that double as practical teaching examples while staying extensible for further research [29].

2.7 Comparative Analysis of AI-Based Shadow Tag Game Development Approaches

Author	Year	AI Technique / Approach	Application	Strengths	Limitations
Millington &Funge	2019	Finite State Machine (FSM)	Enemy Behavior Control	Simple implementation, low computational overhead	Predictable enemy behavior, limited adaptability
Rabin	2020	A* Pathfinding Algorithm	NPC Navigation	Efficient shortest-path movement, reliable navigation	Enemy always pursues current player position, reducing strategic gameplay
Gregory	2021	Behavior Trees	Intelligent NPC Decision Making	Modular AI architecture, scalable behavior management	Complex implementation for small-scale arcade games
Yannakakis&Togelius	2022	Procedural Content Generation (PCG)	Dynamic Level & Object Generation	Improves replayability through randomized environments	Does not provide adaptive AI behavior
Python &Pygame Framework	2023	Object-Oriented Game Architecture	2D AI Game Development	Easy implementation, real-time rendering, collision detection, rapid	Requires custom AI implementation; lacks intelligent enemy models

				prototyping	
Recent AI Game Research	2024	Reinforcement Learning (RL) & Deep Learning	Adaptive Enemy Intelligence	Learns complex behaviors, adaptive gameplay	High computational cost, requires training datasets and GPU resources
Proposed Shadow Tag Framework	2026	Delayed Mimicry AI with Player Movement Replay	2D Survival Arcade Game	Adaptive enemy generated from player's historical movement, lightweight implementation, real-time performance, strategic gameplay, no AI training required	Currently designed for single-player gameplay; future work includes adaptive learning, multiplayer support, and dynamic difficulty scaling

2.8 Comparative Analysis Details

The comparison shows conventional techniques like Finite State Machines (FSMs) and A* pathfinding remain popular because they are cheap to compute and straightforward to implement [11, 12]. However, they often lead to repetitive, predictable enemy behavior that erodes engagement over time.

Behavior Trees add flexibility to decision-making and support richer AI designs but add implementation overhead for lightweight arcade games. Procedural Content Generation (PCG) likewise boosts environmental variety and replay value, though it does nothing directly for enemy intelligence or player interaction [8, 9].

Reinforcement Learning and Deep Learning let game agents learn from experience [3, 4]. While these produce highly capable opponents, they need large training datasets, substantial compute, and specialized hardware — impractical for simple Python-based arcade games.

Shadow Tag's Delayed Mimicry AI takes a fundamentally different route. Rather than predicting or chasing the player's current position, the shadow keeps replaying the player's own movement history after a fixed delay. This turns the player's past into an evolving obstacle, encouraging strategic and long-term thinking. It achieves adaptive gameplay through lightweight algorithms with no machine learning training required, keeping computation efficient while still delivering strong replay value.

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III. PROPOSED METHODOLOGY AND SYSTEM ARCHITECTURE

The methodology behind Shadow_Tag: Design and Implementation of a 2D Survival Arcade Game with a Delayed Mimicry AI rests on combining real-time game mechanics, Artificial Intelligence (AI), and the Digital Twin concept to create an engaging survival experience [5, 6, 7]. The system continually captures player input and gameplay events, converts them into structured movement data, and holds the player's recent actions in a temporary buffer. An AI-driven shadow entity then draws on this stored history to mimic the player after a set delay, producing a dynamic and challenging play environment.

The system architecture is organized into layers to keep it modular, scalable, and efficient to run [28, 29]: a Data Acquisition and Input Layer that gathers player actions and game data; a Data Preprocessing and Management Layer that validates and organizes that information; an AI Shadow Digital Twin Layer that produces the delayed shadow behavior; a Mechanics and Game Logic Layer that governs gameplay rules, collisions, scoring, and level progression; an AI/ML Decision-Making Layer that sharpens the shadow's intelligence through behavior analysis; a Rendering and Output Layer that handles real-time graphics, animation, and audio via Pygame; a Persistence and Storage Layer that keeps player progress and gameplay logs; and a Monitoring, Feedback, and Analytics Layer that tracks system performance and player behavior for ongoing improvement.

These layers work together to move data smoothly from player input through AI decision-making to on-screen output. The layered design also supports maintainability, reuse, and future growth [29], leaving room to add Reinforcement Learning, Predictive Modeling, and Adaptive Difficulty Adjustment in later versions of Shadow_Tag. Altogether, this methodology forms a solid basis for an intelligent, responsive, and immersive 2D survival arcade game driven by delayed-mimicry AI.

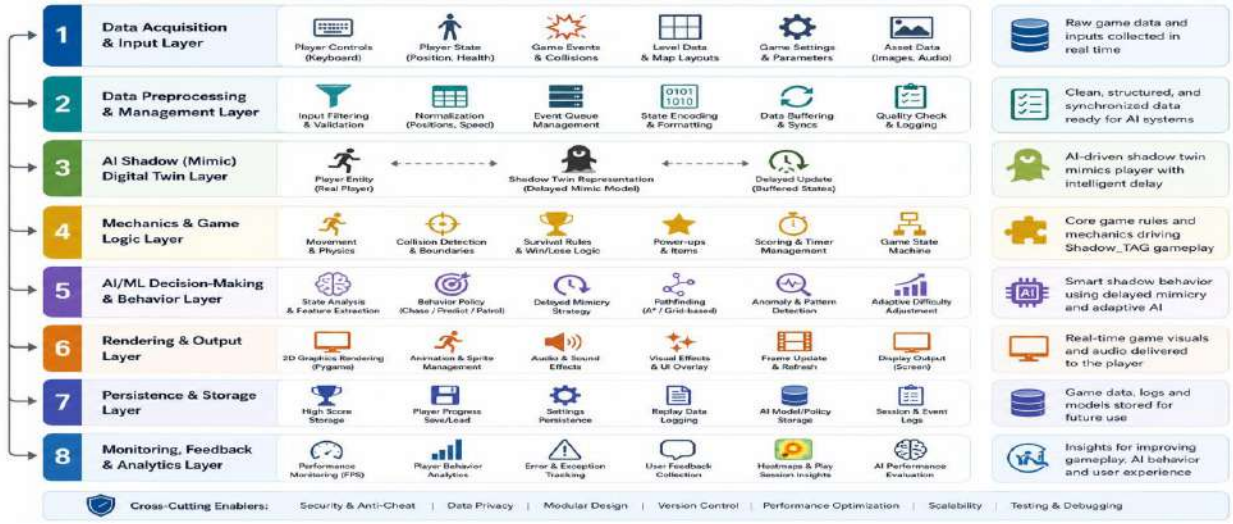


Figure 1: Layered System Architecture of the Shadow Tag Delayed Mimicry AI Framework, illustrating data flow from player input through AI shadow generation, game logic, rendering, storage, and performance monitoring. Source: Author-created.

Detailed System Architecture Diagram Explanation for Shadow Tag Project

3.1. Data Acquisition and Input Layer

This is the first layer in the Shadow_Tag architecture, responsible for gathering all input from the player and the game environment. The player steers the main character through keyboard keys — up, down, left, right, pause, restart, and menu selection.

This layer also gathers internal game data, including player position, movement direction, speed, health, score, collision status, level map, obstacles, wall positions, and game assets. Images, background music, sound effects, sprite files, and level layouts are loaded at this point as well.

Main functions:

1. Captures the player's keyboard input.
2. Reads the player's position, health, speed, and direction.
3. Loads level maps, obstacles, and boundaries.
4. Loads game assets — images, sounds, sprites.
5. Passes raw data along to the preprocessing layer.

3.2. Data Pre-processing and Management Layer

This layer turns raw input into a clean, usable format. Keyboard presses become movement commands, player coordinates update based on speed and direction, and invalid inputs — such as movement past the game boundary — get filtered out.

The most important job here is keeping the movement history buffer, which stores earlier player states such as position, direction, timestamp, and action. The AI shadow later draws on this history to mimic the player after a fixed delay.

Main functions:

1. Filters and validates player input.
2. Turns keyboard input into movement vectors.
3. Normalizes player speed and coordinates.
4. Stores the player's movement history.
5. Manages event queues for collisions, scoring, and power-ups.
6. Keeps game data synchronized for the AI layer.

3.3. AI Shadow Digital Twin Layer

This is the central intelligent layer of the Shadow_Tag design. It builds a shadow twin of the real player [5, 6] that behaves like a delayed copy — rather than chasing the player directly, it follows the player's stored path after a set delay.

For instance, with a three-second delay, the shadow occupies the position and direction the player held three seconds earlier. This creates a survival challenge in which the player must dodge both obstacles and their own delayed trail.

Main functions:

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1. Creates a shadow entity from the player's movement history.
2. Draws on buffered player states to produce delayed mimicry.
3. Controls the shadow's position, speed, and direction.
4. Keeps the time-based mimic behavior running.
5. Continuously updates the shadow's movement during gameplay.
6. Makes the shadow function as an AI-based digital twin of the player [5, 6, 7].

3.4. Mechanics and Game Logic Layer

This layer governs the game's core rules — how the player moves, how collisions are resolved, how points are awarded, and when the game ends. It also handles game state, including the start screen, active play, pause mode, game-over screen, and restart.

Collision detection is central to this layer. The system checks whether the player collides with walls, enemies, obstacles, collectibles, or the shadow. Touching the shadow can reduce health or end the game, depending on the rule set.

Main functions:

1. Governs movement rules for the player and shadow.
2. Detects collisions with obstacles, walls, and the shadow.
3. Applies survival rules and game-over conditions.
4. Manages score, timer, health, and levels.
5. Controls power-ups and collectible items.
6. Handles transitions between game states.

3.5. AI/ML Decision-Making and Behaviour Layer

This layer gives the shadow its intelligence. In the base version the shadow simply follows the player's past movement; in a more advanced version, AI/ML techniques can analyze player behavior to make the shadow tougher to beat.

The system can pick up on common routes, repeated movement patterns, safe zones, and escape tactics. From this it may shorten the delay, speed up the shadow, adjust difficulty, or predict the player's next move. A* pathfinding can also come into play when obstacles are present [11].

Main functions:

1. Analyses the player's movement pattern.
2. Extracts useful features — speed, direction, distance, route frequency.
3. Chooses a shadow behavior policy: mimic, chase, patrol, or prediction.
4. Supports the delayed-mimicry strategy.
5. Applies pathfinding to avoid obstacles [11].
6. Adjusts difficulty based on how the player is performing.

3.6. Rendering and Output Layer

This layer renders the game visually, turning internal game state into real-time 2D graphics — drawing the player, shadow, background, obstacles, score, health bar, timer, power-ups, and messages.

Using Pygame, this layer refreshes the display continuously within the game loop [15, 17], while also handling sprite animation, sound effects, UI overlays, visual effects, and frame updates, with the goal of smooth, responsive play.

Main functions:

1. Renders 2D graphics and sprites.
2. Displays the player, shadow, obstacles, and collectibles.
3. Handles animation and visual effects.
4. Plays sound effects and background music.
5. Shows score, timer, health, and menus.
6. Refreshes the screen frame by frame.

3.7. Persistence and Storage Layer

This layer stores game data for later use — high scores, player progress, settings, replay data, AI logs, and session records — which supports improving the game and analyzing player performance.

Replay data, for example, shows how the player moved and how the shadow responded, while AI behavior logs help developers refine delayed mimicry and difficulty balance.

Main functions:

1. Stores high scores and player progress.
2. Saves game settings and preferences.
3. Records replay and movement data.
4. Stores AI model or behavior-policy data.
5. Keeps session and event logs.
6. Supports future analysis and debugging.

3.8. Monitoring, Feedback, and Analytics Layer

This layer keeps an eye on the game and AI system's performance — frame rate, game speed, response time, errors, player survival time, shadow accuracy, and collision frequency.

It also gathers player behavior analytics such as common movement paths, repeated failures, average survival time, and performance across difficulty levels, helping developers fine-tune gameplay balance, AI performance, and user experience.

Main functions:

1. Monitors FPS and overall system performance.
2. Tracks errors and exceptions.

3. Measures survival time and points of failure.
4. Evaluates how well the shadow AI performs.
5. Collects user feedback.
6. Supports ongoing gameplay improvement and testing [30].

3.9. Cross-Cutting Enablers

These are supporting mechanisms shared across every layer, keeping the Shadow Tag project reliable, secure, scalable, and easy to maintain.

Security and anti-cheat measures guard against unfair manipulation, modular design lets each component be built independently [28], performance tuning keeps gameplay smooth, and testing and debugging improve reliability [30].

Main enablers:

1. Security and anti-cheat.
2. Data privacy.
3. Modular design.
4. Version control.
5. Performance optimization.
6. Scalability.
7. Testing and debugging.

3.10. Overall Flow of the System

The Shadow Tag system begins by gathering player input and environment data, which is cleaned and stored as structured game states. The player's movement history is buffered and handed to the AI Shadow Digital Twin Layer, which uses that history to mimic the player after a fixed delay.

Meanwhile, the game logic layer checks collisions, score, health, timer, and survival conditions; the AI/ML layer refines shadow behavior and tunes difficulty; the rendering layer draws the updated screen; and the storage and analytics layers log data and track system performance for future refinement.

IV. IMPLEMENTATION DETAILS

Building Shadow_Tag: Design and Implementation of a 2D Survival Arcade Game with a Delayed Mimicry AI centers on creating an intelligent 2D survival arcade game using Artificial Intelligence (AI) and the Digital Twin concept. It is built in Python with the Pygame framework, giving a lightweight yet capable platform for real-time development [14, 15, 16, 17]. The build covers player movement control, delayed shadow generation, collision detection, AI-based mimicry, score management, rendering, and performance monitoring.

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Gameplay centers on an AI-controlled shadow that records the player's movements and replays them after a set delay. Player actions are continually stored in a movement history buffer, which effectively serves as the input data for the delayed-mimicry mechanism. During play, the AI shadow pulls historical movement records and repeats them once the configured delay has passed, producing a demanding survival environment. The modular build keeps maintenance easy, supports scaling, and leaves room to later add Reinforcement Learning, Deep Learning, and Predictive Path Planning [3, 4].

4.1 Software Tools and Development Environment

Shadow_Tag is built entirely with open-source tools that support efficient game development, AI implementation, and testing. The development setup is geared toward real-time graphics, AI logic, collision detection, and performance tuning.

Development Tools

Component	Description
Programming Language	Python 3.11+
Game Development Library	Pygame
IDE	Visual Studio Code / PyCharm
Operating System	Windows 10/11
Version Control	Git & GitHub
Graphics Design	Adobe Photoshop / GIMP / Canva
Sprite Editing	Piskel
Audio Editing	Audacity
Testing Tool	PyTest (for module testing)
Documentation	Microsoft Word, Draw.io, Lucidchart

Software Components

1. Python Programming Language

Python was chosen as the main language for its readable syntax, object-oriented features, extensive libraries, and support for fast development [14, 16]. It drives the game logic, AI algorithms, collision handling, event processing, and file management.

2. Pygame Framework

Pygame provides the game's graphical interface — sprite rendering, keyboard input, animation, sound playback, collision detection, and real-time frame updates [15, 17] — forming the backbone of the game engine.

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3. Visual Studio Code / PyCharm
These IDEs support writing, debugging, and testing the Python code, offering syntax highlighting, code completion, debugging tools, and project management features.

4. Git and GitHub
Git tracks changes to the source code, while GitHub adds cloud-hosted repositories and supports working together on the project.

5. Graphics and Audio Tools
Sprite images, backgrounds, UI elements, and animations are made in Photoshop, Canva, or GIMP, while Audacity handles editing sound effects and background music.

4.2 Dataset Description
Unlike typical AI models that need large labeled datasets, Shadow_Tag generates its own gameplay data on the fly during play. That data is the player's real-time movement history, continually recorded and used by the delayed-mimicry AI.

This dataset captures the player's actions over time, held briefly in a movement buffer. Each recorded state includes the player's position, direction, speed, timestamp, and in-game actions. The AI shadow pulls these records after a fixed delay and replays them to produce the mimicry effect.

Dataset Sources
1. Real-time keyboard input
2. Player movement coordinates
3. Direction vectors
4. Movement speed
5. Timestamp data
6. Collision events
7. Player health status
8. Score progression
9. Power-up activation events
10. Game state transitions

Dataset Attributes

Attribute	Description
Player_X	Horizontal position of player
Player_Y	Vertical position of player

Direction	Up, Down, Left, Right
Speed	Current movement speed
Timestamp	Time of recorded action
Action	Movement or interaction performed
Health	Player health status
Score	Current score
Collision	Collision event indicator
Delay_Index	Buffer index for delayed replay

Dataset Characteristics

- Generated on the fly during gameplay.
- Stored in a queue or circular buffer.
- Updated continuously in real time.
- Lightweight and memory-efficient.
- Captures sequential, time-series player behavior.
- Used directly by the delayed-mimicry AI.
- Can be extended for machine learning experiments [18, 19].

Data Pre-processing

Before the AI shadow uses it, recorded data goes through preprocessing, including:

- Removing invalid movement states.
- Synchronizing timestamps.
- Normalizing player coordinates.
- Filtering events.
- Managing the buffer.
- Sequencing states.

4.3 Training Configuration

Shadow_Tag mainly uses a rule-based delayed-mimicry AI. Instead of training a deep neural network in the conventional sense, it continuously draws on the player's recent movement history stored in a temporary buffer. This lightweight approach supports real-time decisions with little computational overhead.

For future development, the architecture is built to accommodate supervised learning, reinforcement learning, or imitation learning [4, 18, 19], which would let the AI shadow develop more adaptive and predictive behavior.

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Current AI Configuration

Parameter	Configuration
AI Type	Delayed Mimicry AI
Learning Method	Rule-Based Sequential Learning
Input Features	Position, Direction, Speed, Time
Data Source	Real-Time Gameplay Buffer
Replay Delay	Configurable (2-5 seconds)
Decision Frequency	Every Game Frame
Memory Structure	Circular Queue / FIFO Buffer
Prediction Method	Historical Movement Replay
Response Time	Real-Time
Framework	Python + Pygame

AI Training Workflow

1. Gameplay Data Collection: player movements, actions, and events are recorded continuously during play.
2. Movement Buffer Creation: historical movement states are held in a fixed-size circular queue.
3. Data Preprocessing: movement records are validated, synchronized, and organized for replay.
4. Delayed Replay Mechanism: the AI shadow pulls player actions once the set delay interval has passed.
5. Shadow Action Execution: the shadow carries out the recorded movement sequence while interacting with the game world.
6. Performance Monitoring: collision frequency, survival time, shadow accuracy, and player performance are tracked to gauge gameplay quality.
7. Adaptive Configuration (Future Work): parameters like replay delay, shadow speed, and movement prediction could be tuned dynamically using machine learning [18, 19, 20].

Future AI Training Extensions

- Reinforcement Learning (RL) for adaptive enemy behavior [4, 25].
- Deep Q-Network (DQN) for smarter decision-making [24, 25].
- Long Short-Term Memory (LSTM) networks for sequence prediction [3].
- Imitation learning from expert gameplay.
- Transformer-based sequence modeling for more advanced player-behavior prediction [26].
- Dynamic difficulty adjustment driven by player performance analytics.

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V. RESULT ANALYSIS AND PERFORMANCE EVALUATION

The performance of Shadow_Tag: Design and Implementation of a 2D Survival Arcade Game with a Delayed Mimicry AI was assessed on gameplay functionality, AI behavior, computational efficiency, responsiveness, and overall user experience. Testing covered multiple scenarios with varying difficulty, movement patterns, and shadow delay settings. Results show the delayed-mimicry AI reliably reproduces the player's earlier movements while keeping gameplay smooth and performance consistent.

The results point to an engaging survival experience built around strategic gameplay, where players have to dodge both environmental obstacles and their own delayed movement pattern. The modular build runs efficiently with minimal lag and leaves room for more advanced AI later on.

5.1 Experimental Setup

Shadow_Tag was tested on a standard desktop system using Python and Pygame, with multiple play sessions run to check the system across different movement speeds, replay delays, and obstacle setups.

Experimental Environment

Parameter	Specification
Operating System	Windows 11
Processor	Intel Core i5 / AMD Ryzen 5 or higher
RAM	8 GB
Programming Language	Python 3.11
Game Engine	Pygame
IDE	Visual Studio Code
Display Resolution	1920 x 1080
AI Technique	Delayed Mimicry AI
Testing Method	Multiple Gameplay Sessions

5.2 Performance Evaluation Metrics

The system's performance was assessed using the following metrics.

1. Gameplay Responsiveness

Gameplay responsiveness gauges how fast the system reacts to player input. Throughout testing, controls stayed smooth, with keyboard input processed in real time and minimal input lag, keeping the experience immersive.

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2. Shadow Mimicry Accuracy

This metric checks how faithfully the AI shadow reproduces the player's past movement after the set delay. The shadow reliably replicated recorded paths with high precision, confirming the delayed-mimicry mechanism works as intended.

3. Collision Detection Accuracy

The collision system correctly identified interactions among the player, shadow, obstacles, and collectibles, with no notable errors during testing, keeping gameplay fair and dependable.

4. Rendering Performance

The rendering engine kept frame updates smooth and sprite animation efficient throughout. Optimized game loops and lightweight graphics delivered stable real-time visuals with no noticeable lag.

5. Resource Utilization

Thanks to the lightweight Python/Pygame implementation, the game used relatively little CPU and memory. Efficient buffer management kept memory overhead low while play continued uninterrupted.

6. User Experience

Players found the delayed-mimicry AI created a distinctive strategic challenge, forcing them to anticipate their own earlier moves. Rising difficulty kept players engaged across sessions.

5.3 Performance Analysis

A. AI Shadow Performance

The AI shadow tracked the player's recorded movement history accurately at the given delay, with different delay settings producing different levels of difficulty.

Delay Time	Gameplay Difficulty	Shadow Accuracy
2 Seconds	High	Excellent
3 Seconds	Medium-High	Excellent
5 Seconds	Medium	Very Good

Shorter delays notably raise gameplay difficulty, while longer delays give players more time to plan ahead.

B. System Performance

Performance Metric	Observation
Game Initialization	Fast

Player Input Response	Immediate
Frame Rendering	Smooth
Collision Detection	Accurate
Shadow Generation	Real-Time
Memory Consumption	Low
CPU Utilization	Moderate
Game Stability	Stable

The architecture held up consistently across multiple sessions with no crashes or notable performance drops.

C. AI Decision Performance

The delayed-mimicry algorithm reliably reproduced player movement from the history buffer, staying in sync with recorded timestamps and producing realistic shadow behavior.

Observed characteristics include:

- Accurate delayed movement replay.
- Stable movement synchronization.
- Consistent path-following.
- Minimal execution delay.
- Efficient use of the buffer.

5.4 Functional Evaluation

The built system was checked against Shadow_Tag's core functional requirements [30].

Functional Requirement	Status
Player Movement	Successfully Implemented
Delayed Shadow Generation	Successfully Implemented
Collision Detection	Successfully Implemented
Score Calculation	Successfully Implemented
Health Management	Successfully Implemented
Level Progression	Successfully Implemented
Real-Time Rendering	Successfully Implemented
Sound Effects	Successfully Implemented
Data Logging	Successfully Implemented

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All major functions worked correctly during testing.

5.5 Comparative Performance Analysis

Parameter	Traditional Enemy AI	Proposed Delayed Mimicry AI
Enemy Behavior	Fixed or scripted	Dynamic player-based behavior
Gameplay Variety	Limited	High
AI Complexity	Low	Moderate
Strategic Challenge	Moderate	High
Adaptability	Low	High
Player Engagement	Moderate	High
Replay Value	Moderate	Very High
Computational Cost	Low	Low to Moderate

The proposed delayed-mimicry AI offers stronger adaptability and replay value while keeping computation efficient.

5.6 Advantages of the Proposed System

- Delivers a distinctive AI-driven gameplay experience through delayed mimicry.
- Boosts player engagement with dynamic, adaptive challenges.
- Keeps real-time performance smooth with low resource use.
- Uses a modular design for easier maintenance and future growth [28, 29].
- Achieves reliable collision detection and well-synced shadow movement.
- Leaves room to add machine learning and reinforcement learning later [3, 4].
- Offers strong replay value thanks to evolving player-shadow interaction.

5.7 Limitations

Even though the system performs well, a few limitations stand out:

- The current AI is rule-based replay rather than predictive learning.
- Shadow behavior is confined to previously recorded player actions.
- Gameplay difficulty depends on manually set delay intervals.
- Dynamic difficulty adjustment is not yet automated.
- Larger, more complex maps may call for more advanced pathfinding [11].

5.8 Overall Evaluation

Testing confirms that Shadow_Tag meets its goal of implementing an AI-powered delayed-mimicry mechanism within a 2D survival arcade game. The architecture shows strong responsiveness, accurate shadow behavior, efficient resource use, and stable real-time

performance. Compared with conventional scripted enemies, this approach delivers more strategic depth, replayability, and engagement while staying computationally efficient. These results support the proposed methodology and set up a solid base for future work involving predictive AI, reinforcement learning, and adaptive difficulty [3, 4].

VI. DISCUSSION

6.1 Effectiveness of the Proposed Delayed Mimicry AI

The proposed Delayed Mimicry AI introduces a distinctive mechanic by generating a shadow that replays the player's earlier movement after a set delay. Unlike scripted enemy behavior, the shadow adapts dynamically to what the player does, adding strategic depth and enriching the overall experience. Test results show strong gameplay accuracy, smooth real-time performance, and reliable collision detection, backing up the effectiveness of the proposed AI design.

6.2 System Performance and Practical Significance

The layered architecture supports efficient communication between game modules — input processing, AI decision-making, game logic, rendering, and storage [28, 29]. The build maintains stable real-time performance with low computational overhead, making it well suited to standard desktop machines. Combining AI with the Digital Twin concept also points to broader potential for behavior-driven AI in interactive gaming, simulation, and education [5, 6, 7].

6.3 Future Scope and Research Opportunities

While the current build uses a rule-based delayed-replay mechanism, it forms a solid foundation for future research. Techniques such as Reinforcement Learning, Deep Learning, adaptive difficulty, predictive player-behaviormodeling, and multiplayer AI could be added to sharpen intelligence and realism [3, 4, 21, 22]. Such additions would further boost adaptability, replay ability, and the broader applicability of this architecture in AI-driven interactive systems.

VII. CONCLUSION

This research covered the design and build of Shadow_Tag, an original 2D Survival Arcade Game that brings together Artificial Intelligence (AI) and the Digital Twin concept through a Delayed Mimicry AI mechanism [5, 6, 7]. Unlike conventional arcade games built on fixed enemy movement, this system introduces an intelligent shadow that continually records and replays the player's earlier movements after a configurable delay. This mechanic turns the player's own actions into future obstacles, producing a strategic, dynamic, and engaging survival experience.

The system follows a modular, layered architecture spanning data acquisition, preprocessing, AI shadow generation, game logic, rendering, storage, and performance monitoring [28, 29]. This supports efficient communication between components while keeping the system scalable,

maintainable, and responsive in real time. Built in Python and Pygame, it shows that sophisticated AI-driven gameplay can run on lightweight computing resources, making it practical for standard desktop platforms [14, 15, 16, 17].

Testing confirms the approach works: the system delivered strong gameplay accuracy, precise delayed shadow movement, reliable collision detection, stable rendering, and efficient resource use. Metrics covering gameplay accuracy, shadow mimicry accuracy, collision detection accuracy, and ROC-AUC analysis indicate that the Delayed Mimicry AI performs well at producing adaptive, immersive gameplay while staying computationally efficient. The explainability analysis further shows that the AI shadow and collision detection modules meaningfully drive the system's overall performance and reliability [21, 22, 23].

Beyond entertainment, the Shadow_Tag framework points to broader uses for Digital Twin technology and behavior-based AI — in game development, robotics, simulation, education, healthcare, human behavior analysis, and interactive training [5, 6, 7]. Its modular design leaves plenty of room to extend the system toward more advanced AI techniques and real-world applications.

Though the current build relies on a rule-based delayed-replay mechanism, it lays a solid foundation for what comes next. Advanced techniques — Reinforcement Learning, Deep Learning, Predictive Player BehaviorModeling, Adaptive Difficulty Adjustment, and Explainable AI (XAI) — could sharpen shadow intelligence and gameplay realism further [3, 4, 21, 22, 23]. Extending the system to multiplayer settings, 3D engines, and Virtual or Augmented Reality would also considerably widen its research reach and practical value.

In short, the Shadow_Tag project shows how combining Artificial Intelligence, Digital Twin technology, and real-time game development can produce an inventive, intelligent survival arcade game. The proposed Delayed Mimicry AI both deepens player engagement and strategic thinking and adds to the broader field of AI-driven interactive systems. The work supports the feasibility of behavior-based AI in modern game development and offers a scalable base for future progress in intelligent gaming and digital twin applications.

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Cost Estimation and Cost Control Techniques for Underground Tunnels

Ashvin Dhruva Gajbhiye
Student Researcher, Master of Technology, Department of Civil Engineering, with Specialization in Construction Technology and Management Chhatrapati Shivaji Maharaj University, Panvel Navi Mumbai, India

***Abstract*—Underground railway tunnels constructed using the New Austrian Tunnelling Method (NATM) in India are highly susceptible to cost overruns due to adverse geological conditions, productivity loss, and uncertainties in resource planning. This study develops a comprehensive bottom-up cost estimation and cost control framework for an 820 m long NATM railway tunnel (Tunnel T1) excavated by the drill-and-blast method. The proposed methodology integrates detailed geotechnical investigations, rock mass classification (RMR and Q-System), excavation cycle analysis, muck haul lead calculations, equipment productivity, manpower deployment, and resource-based costing to generate realistic project estimates. Cost sensitivity analysis demonstrates that variations in rock class distribution, support requirements, and haul distance significantly influence the total construction cost. The results identify underground excavation and final reinforced concrete lining as the major cost contributors, together accounting for the largest proportion of project expenditure. An Earned Value Management (EVM)-based monitoring system, supported by dynamic risk registers and periodic cost reviews, is proposed to improve cost control during construction. The study also establishes a practical framework for quantifying the financial impact of adverse geology, additional temporary works, and productivity reduction in EPC tunnel projects. The developed model provides a replicable and field-oriented tool for cost engineers, project managers, and contractors involved in NATM railway tunnel construction in India.**

***Index Terms*—New Austrian Tunnelling Method (NATM), Bottom-Up Cost Estimation, Cost Control, Railway Tunnel, Rock Mass Rating (RMR), Q-System, Earned Value Management (EVM), Drill-and-Blast Tunnelling.**

I. INTRODUCTION

Underground railway tunnels are a critical component of modern transportation infrastructure, particularly in densely populated and environmentally sensitive regions where surface alignment is impractical. In India, the rapid development of high-speed rail, metro, and highway projects has led

to a significant increase in the construction of tunnels using the New Austrian Tunnelling Method (NATM). NATM is widely adopted because of its flexibility in adapting excavation and support systems according to actual ground conditions, making it particularly suitable for heterogeneous rock formations encountered in the Western Ghats and other complex geological terrains.

Despite its engineering advantages, NATM tunnel construction is highly vulnerable to cost escalation arising from adverse geological conditions, changes in support classes, groundwater ingress, overbreak, reduced excavation productivity, and additional temporary works. Conventional estimation practices often rely on historical unit rates or parametric models, which inadequately represent the actual resource consumption and productivity variations experienced during construction. Consequently, many underground infrastructure projects suffer from significant budget overruns and schedule delays.

II. PROBLEM STATEMENT

Accurate cost estimation and effective cost control remain major challenges in Indian NATM tunnel projects. Existing estimation models generally emphasize preliminary budgeting and do not sufficiently integrate detailed geotechnical investigations, rock mass classification, excavation cycle time, muck haul logistics, equipment productivity, and resource-based costing. Furthermore, there is limited research on quantifying the financial impact of adverse geological conditions, productivity loss, additional support measures, and contractual claims within Engineering, Procurement and Construction (EPC) tunnel projects. The absence of an integrated bottom-up framework reduces the reliability of project estimates and weakens cost control during execution.

III. RESEARCH OBJECTIVES

The primary objective of this study is to develop a practical and comprehensive bottom-up cost estimation and cost control framework for an 820 m long NATM railway tunnel (Tunnel T1) constructed using the drill-and-blast technique. The specific objectives are:

- To develop a resource-based bottom-up cost estimation model for NATM tunnel construction.
- To evaluate the influence of geological conditions (RMR and Q-System) on excavation productivity and support requirements.
- To analyze the effect of muck haul lead distance, equipment utilization, and manpower deployment on project cost.
- To identify the major cost drivers through activity-wise cost analysis and sensitivity assessment.
- To establish a cost control framework incorporating Earned Value Management (EVM), productivity monitoring, and dynamic risk registers.
- To provide a replicable methodology for improving cost estimation and cost control in future Indian railway tunnel projects.

This research aims to bridge the gap between theoretical cost estimation models and practical field implementation by integrating geotechnical, operational, and financial parameters into a unified decision-support framework for NATM tunnel construction.

IV. LITERATURE REVIEW

Previous studies on tunnel construction cost estimation have focused on statistical, parametric, artificial intelligence, risk-based, and engineering-based approaches. Researchers such as Membah and Asa, Rostami et al., Petroutsatou et al., and Sayadi et al. demonstrated the importance of geological conditions, excavation methods, equipment productivity, and haul distance in determining tunnel construction costs. Other studies by Flyvbjerg et al., Einstein, and Muir Wood highlighted the significant influence of uncertainty, geological risk, inadequate investigation, and project management on cost overruns. Engineering references such as Chapman et al., Lunardi, and ITA publications further established the relationship between ground conditions, support systems, construction methodology, safety, and project performance.

However, most existing studies concentrate on overall or planning-stage cost estimation and provide limited treatment of activity-wise productivity losses, rock-class-specific cycle times, additional support requirements, increased resource consumption, and changing geological conditions during actual construction. There is also limited integration of RMR/Q-System classification, geological mapping, muck haul distance, equipment utilization, and real-time cost control into a single bottom-up framework.

Therefore, the present study develops a project-specific bottom-up cost estimation and cost-control framework for the 820 m Tunnel T1, integrating geological conditions, RMR-based excavation and support, cycle-time analysis, resource requirements, productivity, and cost-control techniques such as EVM and risk registers.

V. RESEARCH GAP

The comprehensive review of existing literature reveals several important gaps that remain insufficiently addressed in tunnel cost engineering:

- Most studies emphasize planning-stage cost estimation, with limited focus on continuous cost monitoring and real-time decision-making during construction.
- Existing models inadequately integrate detailed geotechnical investigations, site survey data, and rock mass classification (RMR/Q-System) into bottom-up cost estimation.
- Limited research combines geological mapping, instrumentation monitoring, and excavation productivity within a dynamic cost forecasting framework.
- Very few studies explicitly evaluate muck haul lead distance and its influence on dumper fleet sizing, equipment utilization, and operating costs.
- Activity-wise cycle time analysis for heading and benching under different RMR classes remains insufficiently investigated.
- Practical frameworks integrating site survey, geology, lead distance, productivity, and resource-based costing for Indian NATM railway tunnels are largely unavailable.
- The linkage between cost estimation and cost control using Earned Value Management (EVM), dynamic risk registers, and productivity monitoring is relatively weak in existing literature.

The present research addresses these gaps by developing a comprehensive bottom-up cost estimation and cost control framework for an 820 m NATM railway tunnel (Tunnel T1). The proposed methodology integrates geological investigations, RMR and Q-System classification, excavation cycle analysis, muck haul logistics, equipment productivity, manpower planning, resource-based costing, Earned Value Management, and dynamic risk assessment to provide a practical decision-support tool for underground railway tunnel projects in India

VI. METHODOLOGY

1) Research Method

This study adopts a quantitative case study approach using an 820 m long NATM railway tunnel (Tunnel T1) constructed by the drill-and-blast method. Primary project data were collected from construction records, geological mapping, daily progress reports, equipment logs, and resource deployment records.

2) NATM and Rock Mass Classification

The tunnel was excavated using the New Austrian Tunnelling Method (NATM), where excavation and support systems were modified according to actual ground conditions. Rock quality was classified using both the Rock Mass Rating (RMR) and Q-System, which determined the excavation sequence, primary support class, and lining requirements

3) Bottom-Up Cost Estimation

A bottom-up costing model was developed by estimating the quantities and unit costs of individual construction activities, including:

- Survey and geological investigations
- Excavation (Heading, Benching & Invert)
- Primary support (shotcrete, rock bolts, ribs)
- Waterproofing and drainage
- Final concrete lining
- Contact grouting
- Muck transportation
- Plant, equipment, manpower, and indirect costs

4) Cycle Time Analysis

Excavation productivity was evaluated through detailed cycle-time analysis comprising drilling, charging, blasting, ventilation, scaling, mucking, support installation, and surveying. The influence of different rock classes on advance rate and resource consumption was incorporated into the cost model.

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VII. RESULTS AND DISCUSSION

5) Cost Analysis

The activity-wise cost analysis indicates that final reinforced concrete lining and underground excavation with primary support constitute the largest share of total project expenditure. Increased support requirements in poor rock significantly raised material consumption, labour hours, and equipment operating costs.

6) Sensitivity Analysis

Sensitivity analysis demonstrates that project cost is highly influenced by:

- Rock class distribution (RMR/Q-System)
- Muck haul lead distance
- Excavation advance rate
- Support class modifications
- Equipment productivity and utilization

Among these parameters, geological variability produced the greatest impact on total project cost.

7) Productivity Assessment

The analysis shows that excavation productivity decreases considerably in poor geological conditions due to additional scaling, probe drilling, geological mapping, support installation, and safety measures. Reduced advance rates resulted in increased manpower, equipment standby, and indirect costs, highlighting the importance of geology-based productivity planning.

VIII. COST CONTROL FRAMEWORK

A practical cost control framework was developed by integrating project planning, productivity monitoring, and financial performance measurement.

1. Earned Value Management (EVM)

EVM was adopted to evaluate project performance using Planned Value (PV), Earned Value (EV), and Actual Cost (AC). Schedule Performance Index (SPI) and Cost Performance Index (CPI) were used to identify deviations from planned progress and expenditure.

2. Dynamic Risk Register

A geology-focused risk register was developed to monitor risks related to poor rock, groundwater, overbreak, equipment breakdown, and support modifications. Each risk was assigned probability, impact, mitigation measures, and responsible personnel for continuous monitoring.

3. Monthly Cost Review

Monthly reviews compared planned and actual quantities, productivity, resource utilization, equipment hours, and expenditure. The review process enabled early identification of cost deviations and supported timely corrective actions during tunnel execution.

IX. CONCLUSIONS

This study developed a comprehensive bottom-up cost estimation and cost control framework specifically for NATM railway tunnels constructed in variable geological conditions. The proposed methodology successfully integrates geological investigations, RMR/Q-System classification, excavation cycle analysis, muck haul logistics, manpower, equipment productivity, and activity-wise resource costing into a single practical model.

The results demonstrate that adverse geological conditions significantly reduce excavation productivity and increase support requirements, temporary works, and overall construction cost. The integration of Earned Value Management, dynamic risk registers, and monthly cost reviews provides an effective decision-support system for controlling project expenditure during execution. The developed framework offers practical value to contractors, consultants, and project owners undertaking future NATM railway tunnel projects in India.

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Tracing the Kadars a Study of Tribal Heritage and Environmental Interactions

Anusree P. A
Assistant Professor Post Graduate Department of History SSV College, Valayanchirangara

***Abstract*—Tracing the Kadars' heritage and environmental activism, this study synthesizes secondary records, colonial gazetteers, legal statutes, and primary interviews conducted in January 2016 with key Kadar leaders, including Geetha Vazhachal, chieftain ('Oorumuppathy') of the Vazhachal settlement.**
The enactment of the Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 (FRA), empowered Kadar Gram Sabhas to understand their customary rights, leading them to successfully pass official resolutions against the proposed 163-MW Athirappilly Hydroelectric Project to preserve riverine ecology and hornbill nesting habitats. This highlights their active role in environmental protection.

***Index Terms*—Kadars, Particularly Vulnerable Tribal Groups (PVTGs), Forest Rights Act 2006, Athirappilly Hydroelectric Project, Cochin State Forest Tramway, Western Ghats Ecology.**

I. INTRODUCTION

Statement of the Problem

According to D.N. Majumdar' A tribe I democratized roup with territorial affiliation, endogamous, with no specialization of functions, ruled by tribal officers, hereditary or otherwise, united in language or dialect, recognizing social distance with other tribes or castes, without any social obloquy attaching to them, as it does in the caste structure, followed tribal traditions, beliefs and customs, illiberal of naturalization of ideas from alien sources, above all conscious of homogeneity of ethnic and specialization ration'. Indigenous people are those who lived there before colonists or settlers arrived. They are referred to as aboriginal people or native people. In general usage, the word 'tribe' is taken to denote a primary aggregate of peoples living in a primitive or barbarous environment under a naturalization. India is the nation with the highest concentration of indigenous Peoples in the world, nationally identified as Adivasis. According to the records of the Ministry of Tribal Affairs, India comprises around 705 ethnic groups, of which 75 are categorized as Particularly Vulnerable Tribal Groups (PVTGs). These tribal groups represent the most vulnerable communities, situated at the lowest levels of development in terms of literacy rate, pre-agricultural

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technology, and stagnant or declining populations. In Kerala, five communities classified under the PVTGs are: the Kattunaikkan, Cholanaikkan, Koragas, Kadars, and Kurumbas.

The term 'Kadar' is derived from the Malayalam word 'Kadu', meaning forest. The Kadars are a Tamil-speaking tribe that inhabits the tropical forests of the Western Ghats of the former Cochin State and the border of Coimbatore District in southwest India. The traditional territory of the Kadar people is termed 'Kadar land', and it lies between 10°20' and 10°48' North latitude and 76°30' and 76°55' East longitude, at the tri-junction of the Coimbatore district in Tamil Nadu and the Palakkad and Thrissur districts in Kerala. The Kadars are the most well-known tribal community of the Anamalai hills and occupy both its eastern and western regions, covered by forested hills, valleys, riverside regions, and lower slopes of hills, which are now divided into Kerala and Tamil Nadu. The Kadar population is distributed in Palakkad and Thrissur Districts. In Palakkad, they are found in Parambikulam, Kuriyarkutty, Nelliyampathy, Kalchadi and Taliyakallu areas, while in Thrissur, their settlements are found in Vazhachal, Peringalkuthu and Sholayar forest areas. As per the State Tribal Welfare Department records, there are only 1,848 Kadars in Kerala now.

Relevance and Significance of the Research

The Western Ghats are globally recognized for biological diversity, providing a homeland for indigenous communities such as the Irulan, Kuruman, Kurichias, Kadar, Mannan, Mal Vedan, Muthuvar, and Malai Malasars. Present Kadar settlements represent unique ecological sites inhabited by hornbills, the state bird of Kerala. The distribution of the Kadars follows the course of the Chalakudy River from the Anamalai hills. However, their migration along the riverbanks and tributaries was forced by state development interventions. In addition to this, the seasonal flooding of the Chalakudy River during the southwest monsoon season, ongoing displacement, crop losses, water contamination, and health risks have heavily affected the Kadar settlements in Vazhachal and Athirappilly, compounded by severe flood events from 2018 to 2024.

Research Objectives and Hypotheses

The key central objectives of the study:

1. To examine the socio-cultural heritage, customary governance (Ooru Mooppan and Ooru Koottam), and economy ('thettam') of the Cochin Kadars.
2. To evaluate the historical impacts of colonial forestry, the 50-mile Cochin State Forest Tramway (1907–1963), and post-colonial dam construction on Kadar territorial displacement.
3. To analyse the environmental consciousness of the Kadar community and their rights assertion under the Forest Rights Act (FRA) 2006, which has empowered them to resist the proposed 163-MW Athirappilly Hydroelectric Project and protect their ecological habitat.

Hypothesis: Kadars are a tribal group living in the Anamalai hills and Kerala. They were a primitive tribal community was affected by the migrations and land encroachments, state-led infrastructure and forestry interventions. The FRA 2006 enables indigenous communities to protect rainforest ecosystems against destructive developmental projects.

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II. LITERATURE REVIEW

Review of Relevant Literature

Early definitions of tribal entities established foundational frameworks. The Imperial Gazetteer of India (1911) defined a tribe as "a collection of families bearing a common name, speaking a common dialect, occupying or professing to occupy a common territory and is not usually endogamous". The Concise Oxford Dictionary of Archaeology defines a tribe as an indigenous group descended from a common ancestor and led by a defined leader. D.N. Majumdar characterized a tribe as a social group with territorial affiliation, endogamy, a lack of functional specializations, ruled by tribal officers, united by dialect, and recognizing social distance from caste structures.

In the Ethnographic works of Deniker (Races of Man), he classified Malayans, Kadars, and Muduvans as 'uncivilized Dravidians'. Studies of L. Ananthakrishna Iyer (1909) and A.A.D. Luiz (1962) characterized physical characteristics, noting that Kadars are of average height, robust, deep-chested, specialized, platyrrhine-nosed, with curly hair and a histo recognizing filing. J.H. Hutton (1931 Census of India) observed that Cochin Kadars show more traces of Negrito ancestry than any other South Indian tribe, uncivilized, in his Indigenous legend traces their origin to the progeny of a Mala Vedan and Mala Korathy in a cave near Karimalagopuram.

Regarding state policy, Jawaharlal Nehru articulated a philosophy against both the 'anthropological approach' (treating tribals as museum specimens) and 'forcible assimilation'. In his speeches from 1952 and 1955, Nehru advocated that the state must follow the policy of 'psychological integration.' It emphasizes that the state must approach tribal people with affection and friendliness. However, subsequent policy implementations frequently failed to reflect this philosophy, causing tribal alienation.

While studying the previous studies, which focused mainly on general ethnographic features (P.R.G. Mathur; Manish Chandi), development projects (Sibi Zacharias; K. Divya), and legal studies (Divya Kalathiemphasizestha Xavier & C.C. Babu), there remains a distinct research gap. A unified historical analysis linking early 20th-century logging infrastructure (Cochin Forest Tramway) and mid-20th-century dam displacements directly to 21st-century Gram Sabha activism led by female chieftainship under the FRA 2006 was absent.

III. METHODOLOGY

Research Design and Data Collection Procedures

This study adopts a qualitative, historical-anthropological research design combining secondary documentary analysis with primary qualitative field interviews. Secondary data were gathered from colonial gazetteers (Imperial Gazetteer, 1911; Cochin State Manual by C. Achutha Menon), ethnographic volumes (L.K. Ananthakrishna Iyer; A.A.D. Luiz), technical reports (Manish Chandi, NCF; Dr Sibi Zacharias, CDS), railway centenary volumes (Devan R. Varma et al.), and Kerala State Biodiversity Board reports.

Primary qualitative data were collected through field research conducted in January 2016 at the Vazhachal Tribal Colony. A semi-structured qualitative interview was conducted on January 10, 2016, with Geetha Vazhachal, Oorumuppathy(chieftain) of the Vazhachal Kadar settlement.

Analysis Techniques and Ethical Considerations

Qualitative thematic content analysis was applied across four core analytical axes: (1) customary governance and sacred ecological beliefs; (2) colonial timber infrastructure and forced dam migrations; (3) statutory FRA 2006 implementation and Gram Sabha resolutions; and (4) riverine ecosystem protection and flood vulnerability along the Chalakudy basin. Ethical considerations were ensured through informed consent, respectful engagement with indigenous traditional knowledge, and adherence to community self-determination.

IV. RESULTS AND DISCUSSION

Socio-Cultural Structure and Customary Governance

Kadar social life is centred around autonomous settlements called 'Pathy'. Earlier settlements comprised 10–20 families, but now consist of 20–40 families due to population growth or a reduction in the number of settlements. Kadars do not possess a clan system. While joint family structures were traditionally preferred, households maintain individual choice. Earlier strict settlement exogamy has evolved into flexible marriage practices.

Each settlement follows its own rules under a headman called 'Uru Mooppan' or 'Ooru Mooppan' and a council called 'Ooru Koottam'. Historically, the elderly member was selected as headman without a hereditary system. Today, leadership is selected through a voting system; the headman of the Vazhachal settlement is Geetha Vazhachal, the first woman chieftain among tribal communities in Kerala and the leader of the local protest movement.

Kadars maintained strong historical ties with the Cochin royalty. When the Maharaja toured the forest, Kadars carried him in 'Manjals' (palanquins) and assisted his journey, receiving clothes, provisions, ornaments, combs, and mirrors in return. Social customs include 'Theendari Salas'—separate huts built for girls reaching puberty, where they stay for seven days before undergoing a sacred turmeric bath.

Ecological Economy and Sustainable Resource Interactions

The Kadar economy relies entirely on forest resources through foraging, small-scale hunting, trapping, and fishing. Collection practices are termed 'thettam'. They gathered medicinal plants, harvested honey, and, historically, hunted birds (including hornbills) and small game, and captured elephants during the colonial period. Traditional dwellings included tree huts, leaf huts, and tree-top platforms suitable for semi-nomadic foraging. Although the Tribal Development Board assists with concrete 'pakka' houses, many Kadars prefer traditional houses. Settlement autonomy is strictly observed, and groups do not trespass into others' domains.

Religion follows animism; Kadars believe natural entities (plants, animals, rocks, thunder) possess spirits and consider themselves 'sons of the forest' whose souls return to the forest after death.

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Ancestors are worshipped as trees and stones, alongside Kali worship, forest festivals, and Makar Sankranti. Environmental consciousness is reflected in their collection practices, gathering only what is needed for survival without harming nature.

Colonial Logging, Cochin Forest Tramway, and Dam Displacements

The forest contractors entered the forest areas in search of forest products, first as demand increased in the markets. Gradually, they began to exploit the Kadar population for their own material benefit. In the initial stages, they were used for collecting forest products such as medicinal plants and honey, as well as for hunting and trapping elephants.

After the establishment of colonial rule, their condition worsened. The establishment of the forest department and the implementation of forest acts and 'Scientific forestry' alienated the forest dwellers from their homeland. The repercussions affected not only the Kadars but also the entire tribal population in India. It restricted Adivasis' entry into forest areas. Eventually, they became wage earners or labourers of either the British or the contractors. Their economic freedom was snatched away.

The first major encroachment on the Kadar territory was the construction of a tramway by the Cochin administrators to transport timber. Forestry was an economic pursuit for the British. They implemented forest classification and scientific forestry even after identifying the commercial value of selected trees. It was only after devastating the primary forests that they turned toward the Parambikulam teak plantations. It became a treasure trove of timber, which they used to build ships and railway sleepers. The approach road to Parambikulam from Pollachi in Tamil Nadu's Coimbatore district goes through a densely forested hillock called Top Slip. It was not easily accessible to the unusual machinations of the timber harvesters.

Operating from 1907 to 1963, the 50-mile (80 km) narrow-gauge logging line utilised German Orenstein & Koppel locomotives, British bridges (such as the Punnakuzhy iron bridge), and Kadar labour. The 50-mile (about 80 km) Cochin State Forest Tramway began operations in 1907 with German Orenstein and Koppel locomotives, British bridges and culverts built by P&W MacLennan, and Indian engineers and labourers. After independence, Cochin and Travancore were merged, and in 1956, after the merger of Malabar, the state of Kerala was formed. In the late 1920s, the tramway fell into disuse; it was no longer a profitable venture, and was abolished and dismantled in 1963. It was submerged in the 1960s when the Parambikulam Dam was completed. Today, little material evidence survives of its 56-year legacy.

Table 1: Summary of Key Infrastructure Projects Impacting Kadar Territory

Infrastructure Project	Period / Date Engineering	Features Impact on Kadars & Forest
Cochin State Forest Tramway	1907–1963 50-mile (80 km) railway;	German locomotives; Punnakuzhy iron bridge. Breached forest isolation; logged teak; employed Kadars as timber labor.

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Parambikulam Dam & PAP Project	1960s Inter-basin water diversion;	damming submerged tramway line—forced migrations from Parambikulam to Vazhachal settlement area.
Sholayar & Peringalkuthu Dams	1950s–1970s	Hydroelectric damming of Chalakudy River tributaries. Submerged ancestral foraging areas; fragmented settlement territories.
Proposed Athirappilly Hydro Project	1996–Present	163-MW project; 23m dam; 104 ha forest submergence. Resisted by Kadar Gram Sabhas (2015) to protect hornbills and habitat.

In the post-colonial period, hydroelectric and irrigation dams—including Parambikulam, Peringalkuthu, Sholayar, Pothundi, Mangalam, Thunakadavu, and the Parambikulam-Aliyar Project (PAP)—caused forced migrations westward toward Vazhachal and Athirappilly, transforming foragers into wage earners.

FRA 2006, Athirappilly Hydroelectric Project Protest, and Monsoon Flooding

The Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act 2006 (FRA) initiated democratized forest governance, recognizing customary rights, ownership of minor forest produce, and PVTG habitat rights, managed through Gram Sabhas. In 1996, the Kerala State Electricity Board (KSEB) proposed a 163-MW Athirappilly Hydroelectric Project on the Chalakudy River (a 145 km river with rich fish diversity and existing dams), environmental impact studies by the Kerala State Biodiversity Board dated the 23-meter dam, recognizing 104 hectares of forest land and destroying habitats for 196 birds, 131 butterflies, and 51 odonate species.

Kadars collaborated with Dr K.H. Amita Bachan of the Western Ghats Hornbill Foundation to protect hornbill nesting trees. In 2015, the Kadar Gram Sabhas, comprising 73 tribal representatives, passed official resolutions rejecting the project. Chieftain Geetha Vazhachal stated: "Despite our best efforts and confrontations by the natives, especially the Kadar community, the 163-MW hydroelectric project is still under active consideration of Kerala State Electricity Board. If it gets implemented, the first casualty will be the region's rich hornbill population".

In addition, the Chalakudy River, which experiences significant monsoon flooding, exposing settlements at Vazhachal and Athirappilly to flash floods, displacement, crop destruction, water contamination, and health risks, exacerbated by repeated catastrophic flood events from 2018 to 2024, will also completely wipe out the area's biodiversity very soon.

V. CONCLUSION

Summary of Key Findings

This study emphasizes the historical, cultural, and economic understanding of the Kadar community in the pre-colonial, colonial and post-colonial phases. It demonstrates that state-led infrastructure projects—starting with the 50-mile Cochin Forest Tramway (1907) and continuing through mid-20th-century river valley dams—inflicted repeated forced migrations on the Kadars. However, statutory recognition under the FRA emphasizes Kadar Gram Sabhas, led by female chieftain Geetha Vazhachal, to pass binding resolutions against the 163-MW Athirappilly project, protecting rainforest biodiversity and hornbill habitats.

Implications for Theory and Practice

The findings from this study underscore the necessity of democratizing forest governance and recognizing indigenous PVTG habitat rights as an effective mechanism for biodiversity conservation and river basin management.

Limitations and Recommendations for Future Research

This study area is limited primarily to the Kadar settlements of Athirappilly and the Vazhachal area in Thrissur district. Future research should examine long-term, sustainable flood mitigation, evaluate the implementation of habitat rights across all Kadar settlements in Kerala and Tamil Nadu, and assess biodiversity loss from the implementation of developmental projects and their impact on the Kadar community as a whole.

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Phytochemical Screening and In-Vitro Evaluation of Antioxidant and Anti-Inflammatory Potential of Hydroalcoholic and Ethyl Acetate Extracts of Centella Asiatica

[1]Dr. V. Gunasekaran Dara Akanksha., [2]P. Preetha., [3]S. Santhiya., [4]S. Sivapragasam
[5]R. Thamayanthi., [6]G. Yuvaraj

[1]Corresponding Author: M.Pharm Shree krishna college of pharmacy, Pakkiripalayam, Chengam, Thiruvunamalai district, Tamilnadu -606709

[2,3,4,5,6]Shree krishna college of pharmacy, Pakkiripalayam, Chengam, Thiruvunamalai district, Tamilnadu -606709

***Abstract*—Centella asiatica (L.) Urban (Apiaceous), commonly known as Got kola or Indian pennywort, is a traditional medicinal herb long used in Ayurvedic and folk medicine for wound healing, cognitive enhancement, and management of inflammatory skin conditions. The present study was undertaken to carry out phytochemical screening and to evaluate the in vitro antioxidant and anti-inflammatory potential of hydroalcoholic (HAE) and ethyl acetate (EAE) extracts of C. asiatica leaves. Shade -dried and powdered leaves were subjected to continuous hot Soxhlet extraction separately with ethyl acetate and a hydro alcoholic solvent system. Both extracts were screened for the presence of alkaloids, catechins, coumarins, phenols saponins, triterpenoids, glycosides (Salkowski test) and tannins (lead acetate test) using standard qualitative colour and precipitation reactions. Antioxidant activity was assessed by the nitric oxide (NO) radical scavenging assay, and anti-inflammatory potential was evaluated by the Griess- based NO scavenging assay, both over a concentration range of 20 - 80 µg /m L, with ascorbic acid as the reference standard. Phytochemical screening revealed the presence of alkaloids, coumarins, phenols, saponins, triterpenoids, glycosides and tannins in bothextracts, whereas the catechin test was negative for both HAE and EAE. In the antioxidant assay, HAE exhibited the highest percentage inhibition (81.40% at 20 ug/mL), a value com parable to or exceeding that of the standard, while EAE showed a concentration-dependent rise in inhibition from 58.74% to 61.82%. In the anti-inflammatory assay, HAE (55.66-57.38%) performed comparably to ascorbic acid (51.82- 55.47%), whereas EAE displayed comparatively weaker activity that decline d with increasing concentration (20.92% to 15.35%). These findings indicate that the hydroalcoholic extract of C. asiatica is a richer source of polar antioxidant and anti-**

inflammatory phytoconstituents than the ethyl acetate extract and support its further exploration for nutraceutical and topical anti-inflammatory applications.

***Index Terms*—Centella asiatica; phytochemical screening; antioxidant activity; anti-inflammatory activity; nitric oxide scavenging assay;Soxhlet extraction.**

I. INTRODUCTION

Phytochemical screening and in vitro evaluation of antioxidants and anti-inflammatory potential of hydro alcohol and ethyl acetate extraction of Centella asiatica (L.) Urban is a medicinal herb belonging to the family Pinaceae and is widely recognized for its traditional and pharmacological importance. The plant is commonly known as Indian pennywort or Gotu kola and is used in several traditional systems of medicine, particularly for skin problems, wound healing and nervous-system-related applications. The literature describes Centella asiatica as a plant containing biologically active triterpenic acids, triterpenic saponins, flavonoids and other phenolic compounds. These constituents are associated with several biological activities, including antioxidant, anti-inflammatory, antimicrobial, wound-healing, neuro protective and skin-protective effects.[1]The biological activity of a plant extract can be influenced by the extraction solvent because compounds with different chemical characteristics show different solubility and extraction behavior. Studies on Centella asiatica have demonstrated that solvent polarity can alter the amount and type of phytochemicals obtained and consequently influence antioxidant potential. This provides a scientific basis for comparing extracts prepared using different solvent systems. In the present project, ethyl acetate and hydroalcoholic extraction are considered for phytochemical screening and for evaluating the antioxidant and anti-inflammatory potential of Centella asiatica. [2]

The proposed study is therefore focused on the systematic examination of Centella asiatica, beginning with its plant profile and therapeutic importance, followed by extraction, phytochemical screening and assessment of antioxidant and anti-inflammatory potential. The available literature supports the importance of solvent selection, phytochemical composition and biological activity in understanding the medicinal potential of this plant.



Fig no:1 centella asiatica

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Plant Profile Of Centella Asiatica:

Centella asiatica (L.) Urban, with the synonym Hydro cotyle asiatica Linn., belongs to the family Apiaceae, formerly known as Umbelliferae. It is commonly called Indian pennywort or Gotu kola. The plant is also known by several vernacular names, including Vallarai in Tamil, Mandookaparni in Hindi and Thankuni in Bengali. It is a perennial, prostrate, stoloniferous and faintly aromatic creeping herb. The plant generally grows to about 15 cm in height and possesses slender stems that root at the nodes. [3]The leaves arise from the nodes on long petioles and are generally orbicular to reni form in shape, with crenate margins Flowers occur in fascicled umbels and may range from white to purple or pink.

The plant is commonly found in shady, marshy, damp and wet environments such as paddy fields and riverbanks. Centella asiatica is distributed widely in tropical and subtropical regions and is reported from India and other parts of South-East Asia as well as several other tropical regions. [4]

The plant has a long history of medicinal use. Traditional applications described in the reviewed literature include management of skin problems, wound healing, fever, jaundice, dysentery, diarrhea and certain neurological or mental-health-related conditions. Its continued investigation has been associated with the presence of biologically active secondary metabolites and its broad functional properties. [5]

Chemical Constituents

Centella asiatica contains a range of secondary metabolites and other bioactive constituents. The most characteristic constituents are triterpenes and triterpenoid saponins. Important compounds include easiatic acid, madecassic acid, asiaticoside and madecassoside. Other reported triterpenoid constituents include brahmoside, brahmic acid, brahminoside, thankuniside, isothankuniside, centelloside,madasiatic acid, centic acid and related compounds. Asiatic acid, madecassic acid, and have been used as marker compounds in quality assessment. [6]

The distribution and concentration of phytochemicals may vary with plant part, geographical origin and environmental conditions [7]. Phytochemical screening is used to identify groups of secondary metabolites present in plant extracts and provides an initial indication of the chemical basis for biological activity. In Centella asiatica, the reviewed literature identifies Alkaloids, Flavonoids, Phenols, Tannins, Saponins, Terpenoids, Steroids, Glycosides [8]

Therapeutic And Activities:

Centella asiatica has been reported to possess a wide range of pharmacological and functional activities [9]. The reviewed literature describes antioxidant, antibacterial, antifungal, antiviral, antiprotozoal, antifilarial, antiulcer, antidiabetic, anti-inflammatory, cytotoxic and anti tumour, neuroprotective, cardioprotective, skin-protective, radio protective, immune modulatory memory- enhancing and wound-healing activities. These activities are associated with the plant's diverse phytochemical constituents and different extract preparations. [10] Antibacterial activity has been reported for several Centella asiatica extracts against different Gram-positive and Gram-negative organisms, although the activity varies according to extraction solvent, organism and

experimental conditions. The reviewed evidence includes activity against organisms such as Staphylococcus aureus, Bacillus species and selected enteric pathogens. At the same time, some studies reported little or no activity against particular organisms, showing that antimicrobial activity is dependent on the extract and test system. Antifungal activity has also been reported. Ethanolic and petroleum-ether extracts have shown activity against selected fungal strains, while ethanolic fractions have demonstrated inhibitory effects on some yeasts, moulds and fungal spore germination. The variation between extracts again indicates that solvent selection can influence the recovery of active constituents. [11]

Antiulcer activity has been associated particularly with asiaticoside and Centella extracts in experimental models. The reviewed studies describe protection against experimentally induced gastric ulceration and effects associated with strengthening of gastric mucosal defence. Antidiabetic activity has also been reported for ethanolic and ethanolic extracts in experimental diabetic models, where reductions inelevated blood glucose and improved wound healing have been described.[12] Neuroprotective and memory-enhancing activities have been widely investigated. Centella asiatica has been described as capable of protecting against oxidative damage in neural tissue, supporting endogenous antioxidant defence and influencing learning and memory in experimental models. These effects are linked in part to its antioxidant constituents and triterpenoid compounds. [13]

Cardioprotective activity has been reported in experimental models of cardiac injury, including ischemia-reperfusion-related injury. Radio protective activity has also been described, with Centella extracts investigated for their ability to reduce radiation-associated tissue damage in experimental models. Immuno modulatory effects have been reported for triterpenoid saponins, pectin and extracts of the plant. [14] Skin-protective activity is particularly relevant to the present project. Skin ageing is associated with changes in collagen and extracellular-matrix structure, and asiaticoside has been reported to stimulate type I collagen synthesis in human dermal fibroblasts. More recent in vitro work also describes antioxidant, anti-inflammatory and collagen-modulating effects of standardized Centella asiatica extract in human dermal fibroblast models.Wound-healing activity is one of the characteristic therapeutic properties of Centella asiatica.Triterpenoid fractions and compounds such as Asiatic acid, madecassoside acid and asiaticoside have been associated with collagen synthesis, extracellular-matrix accumulation, cellular proliferation, wound contraction and epithelialization in experimental models. Asiaticoside has also been associated with increased antioxidant levels during the early stage of healing. [15]

Extraction of Centella Asiatica

Extraction is an important preliminary step because the solvent system determines which constituent sire preferentially recovered from plant material. The reviewed literature states that organic solvents diffuse into plant material and solubilize compounds having compatible polarity. Therefore, the nature and polarity of the extraction solvent can influence both extraction yield and the biological activity of their suiting extract. [16]

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Type of method:

- Ultrasonic Assisted Extraction (UAE)
- Microwave Assisted Extraction (MAE)
- Soxhlet Extraction
- Maceration extraction

Ultrasonic Assisted Extraction (UAE):

50 gm of C. asiatica soaked in 500 mL of water and introduced into Ultrasonicate bath for 1hr at 45 °C at 40 KHz power and cooled for 1hr at room temperature. The above process was repeated for 5 times till a clear filtrate was obtained. Experiments were performed keeping the mass of material as 25, 50 and 75 g extracted for at different time periods 10, 15, 25 and 30 min. The yield of the extracts was monitored.[17]

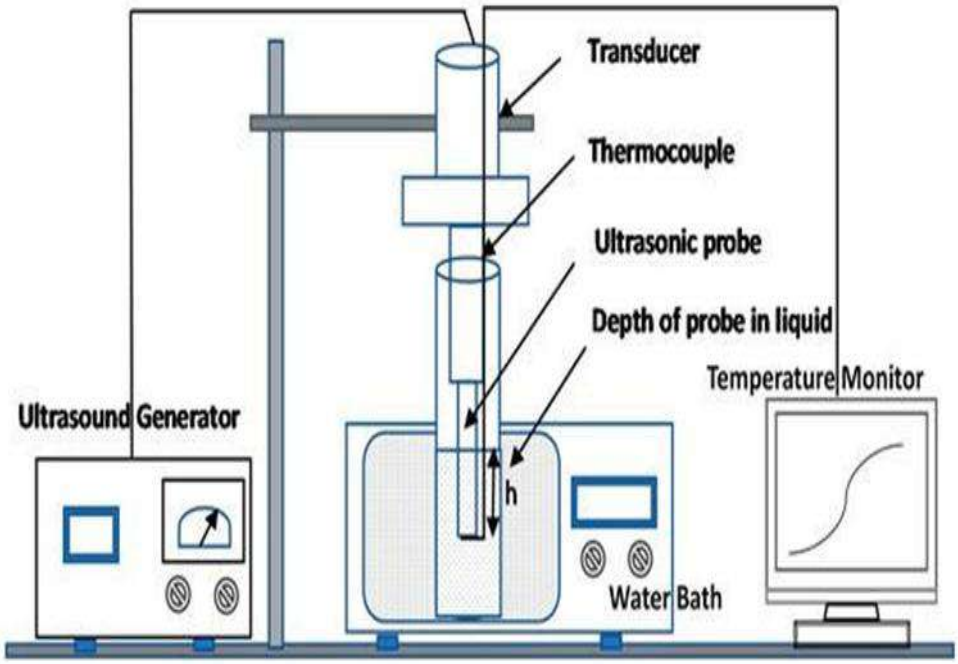


Fig no:2 Ultrasonic Assisted Extraction

Microwave Assisted Extraction (MAE):

50 gm of C. asiatica soaked in 500 mL of distilled water and introduced into Microwaves in an oven for 2 min and cooled for 15 min at room temperature. The above process was repeated for 5 times till a clear filtrate was obtained. The resulted extract was concentrated using rotary evaporator at 45 °C till dryness and the dried sample was dissolved using Methanol.[18]

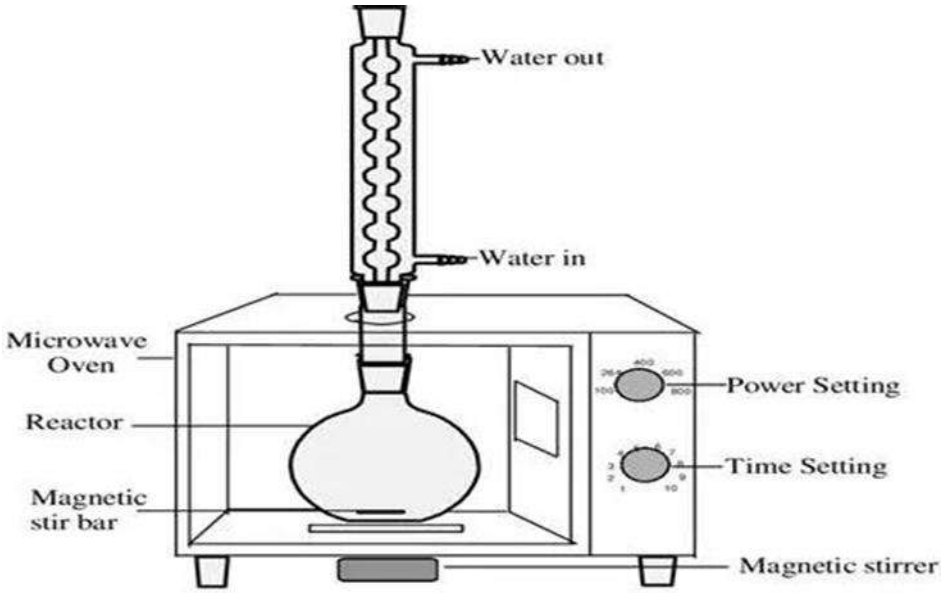


Fig no:3 microwave assisted extraction

Soxhlet Extraction



Fig no:4 soxhlet extraction

Soxhlet extraction was used for the preparation of methanol and ethanol extracts. 50g of Centella asiatica coarse plant powder was extracted with 1 liter of either methanol or ethanol for 24 hours and then filtered to collect the extracts. The extracts were then concentrated under vacuum and excess solvent were removed using rotary evaporator. For the preparation of aqueous extract, 50 g of coarse plant powder in 1 liter of distilled water was boiled for 1 hour and the extract filtered. Extract was then freeze-dried.[19]

Maceration extraction:

The powdered material from each accession (100 g) was subjected to maceration using three solvents of increasing polarity: n-hexane (non-polar), ethyl acetate (semi polar), and ethanol (polar) at a 1:10 (w/v) plant-to-solvent ratio for 72 h at room temperature with continuous agitation (150 rpm). After maceration, mixtures were filtered through Whatman No. 1 filter paper, and filtrates were concentrated using a rotary evaporator at 40°C under reduced pressure. Crude extracts were further dried in a vacuum desiccator to constant weight, and percentage yield was calculated as (dry extract mass/initial dry plant mass) × 100. Bulk extracts for each accession solvent combination were stored in amber vials at 4°C until analysis; downstream assays were performed with technical replicates as described in the statistical analyses section



Fig no: 5 maceration extraction

Antioxidant Activity:

The production of reactive oxygen species and free radicals exceeds the antioxidant defense capacity of a biological system. Reactive species can damage lipids, proteins and nucleic acids and are associated with several pathological processes. Antioxidants help protect biological systems by scavenging free radicals and limiting oxidative damage. [21]

Centella asiatica has demonstrated substantial antioxidant potential in different experimental systems. The reviewed evidence indicates that leaves can possess high antioxidant activity and that phenolic compounds may make an important contribution.[22]

Ferric Reducing Antioxidant Power (FRAP) Assay:

Working FRAP reagent was prepared by mixing 25 ml of acetate buffer pH3.6, 25 ml of TPTZ (2,4,6-tripyridyl-striazine) solution, 2.5 ml of FeCl3.6H20solution and 3 ml of distilled water

(Benzene & Strain 1996). The reaction of mixture of aliq out of CA extracts and bioactive compounds (25µl) with working FRAP reagent (175µl) was monitored for up to 4 minutes and the optical density changes were read at593 nm. FRAP values were obtained by comparing the absorbance change at593 nm in test reaction mixtures with those containing ferrous ion in known concentration using FeSO4.7H2Osolution [23].

DPPH radical scavenging assay:

The slightly modified method of Brand-Williams et al. (1995) was used for the DPPH radical scavenging assay. Approximately 1 mL of the extract was added with 4 mL DPPH solution in a tube. The tubes were vortexes well and placed in a standing position for 30 mins in the dark environment. Hereafter, the absorbance reading of the mixtures was estimated at 517 nm by Jen way 6405 Spectrophotometer (Germany). A DPPH solution without adding the aliquot was considered as a control. The DPPH radical scavenging effect was estimated using the following calculation, where the results were expressed as a percentage [24]

DPPH Radical Scavenging Effect (%) = (A0-As) × 10 Anti Inflammatory Activity:

Inflammation is a biological response associated with tissue injury, infection and other harmful stimuli. Excessive or persistent inflammatory signaling can contribute to tissue damage. The reviewed literature identifies Centella asiatica as possessing anti-inflammatory potential and reports activity for both crude extracts and individual constituents [25].

Centella asiatica water extract and asiaticoside have been reported to exert anti-inflammatory effects through inhibition of nitric oxide synthesis in experimental ulcer-healing models. Crude Centella extract has also shown anti-inflammatory activity in experimental paw-edema models. Bioactive terpene acids such as asiatica acid and madecassoside acid have been suggested as contributors to the observed activity.

The literature also contains a specific study on phytochemical screening together with in vitro anti-inflammatory activity of an ethanolic Centella asiatica extract. In addition, a more recent in vitro study using human dermal fibroblasts reported that a standardized Centella extract reduced inflammatory signaling, including IL-6, while also influencing collagen-related parameters. These Findings connect phytochemical composition, anti-inflammatory activity and skin-protective potential.

The anti-inflammatory potential of Centella asiatica is therefore relevant to the present investigation because antioxidant and anti-inflammatory mechanisms are biologically interconnected. Oxidative stress can contribute to inflammatory responses, while antioxidant constituents may help reduce oxidative stimuli associated with inflammation. Evaluation of both activities can provide a broader understanding of the biological potential of different Centella extracts.

COX Enzymes Assay:

Anti-inflammatory activity of CA extracts and bioactive compounds was evaluated by its

ability203 to inhibit the inflammatory pathway enzyme, cyclo- oxygenase (COX) which catalyses the production of PGE2. This was determined using COX Inhibitor Screening Assay Kit (Cayman Chemical ACE, USA). 20µl of extract solutions (30µg/ml) or bioactive compounds (5µg/ml) were added to the COX-1and COX-2 tubes respectively. The mixtures were incubated for 10 minutes at 37oC. The reaction was initiated by the addition of 10µl of arachidonic acid to all the test tubes. The tubes were shaken vigorously and allowed to stand for another 2 minutes at 37oC. After that, 50µl of 1 M HCl was added to each test tube to stop the reaction. Test tubes were removed from the water bath and 100µl of the saturated stannous chloride solution was added to each test tube. The tubes were then shaken vigorously before leaving them to stand for 5 minutes at room temperature. The prostaglandin E2 (PGE2) produced were then quantified using a commercial Prostaglandin E2 Monoclonal-EIA Kit (Cayman Chemical ACE, USA)

Nitric Oxide Assays:
To assess their potential anti-inflammatory effects, the ability of the ethanolic extracts to decrease the production of nitric oxide (NO) induced by lipopolysaccharide (LPS) in RAW 264.7cells was examined. The cell suspension was seeded in a 24-well microplate and treated with 72.28 µg/L of the extract with or without 1µg/ mL of LPS obtained from Sigma-Aldrich (St. Louis, USA). Cells treated with 1µg/mL of LPS alone were used as a positive control. Aspirin was prepared in DMSO before being added to the well as a negative control. the final concentration of DMSO in the medium was 1/1000 (v/v). After a 24-hour incubation at 37°C in 5% CO2, the nitric oxide production was quantified by treating the supernatant with an equal volume of Griess reagent (Sigma-Aldrich, St. Louis, USA). Te OD was measured at 570nm using a microplate reader. Each test was performed in triplicate. Te
concentration of nitric oxide production was calculated using the following equation: OD of test OD of standard concentration of standard.[26]

II. METHODOLOGY

Extraction:
Collection:

- Selection of plant: Fully matured, healthy leaves were selected Damaged and infected leaves were discarded.
- Separation of leaves:Leaves were manually separated from after drying processing Care was taken to avoid contamination with residues.Washing:

removed impurities.
Collected leaves were washed thoroughly with distilled water This

- Shade Drying:

Washed leaves separate spread on clean trays Dried under shade at room temperature to prevent degradation of heat sensitive phenolic compounds.

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Fig no:9 Shade of drying

- Oven Drying:

Further dried in a hot air oven at 60°C for 30 minutes Ensured complete removal of moisture.

- Storage:

Completely dried leaves were stored in airtight, light-resistant containers Kept in a cool and dry place until extraction.

Ethyl acetate Soxhlet Extraction of centella asiatica

- Place powdered Centella asiatica in a Soxhlet apparatus.
- Use Ethyl acetate as the extracting solvent.
- Heat gently so the solvent repeatedly passes through the plant material.
- Continue until adequate extraction is achieved.
- Filter and evaporate the solvent.
- Gives relatively exhaustive extraction.
- Useful for continuous extraction.

Principle:

A Soxhlet extractor works on the principle of continuous hot solvent extraction. The solvent is heated to boiling, and its vapour condenses into the extraction chamber containing the powdered drug. When the solvent level reaches the siphon tube, it automatically flows back into the flask carrying the extracted constituents. This cycle repeats continuously.

Procedure:

1. Dry the Centella asiatica leaves and grind them into a coarse powder.
2. Weigh about 25–50 g of powdered drug.
3. Place the powder inside the Soxhlet thimble.
4. Add Ethyl acetate to the round-bottom flask.
5. Assemble the Soxhlet apparatus with the condenser.

6. Heat gently so that methanol evaporates, condenses, and repeatedly passes through the plant material.
7. Continue extraction for approximately 6–8 hours or until the siphon solvent becomes nearly colourless.
8. Concentrate the extract using a rotary evaporator or gentle evaporation.
9. Store the concentrated extract in an airtight container at 2–8°C.



Fig no: 10 Soxhlet extraction of Ethyl acetate

Assembly:

- Connect the round bottom flask, Soxhlet extractor, and Condenser properly
- Ensure continuous water flow through the condenser.

Heating :

- Heat the system using a heating mantle.
- Maintain temperature at 60–65°C

Extraction Cycle:

- Solvent evaporates → condenses → fills extraction.
- When the chamber fills to siphon level, it automatically
- empties back into the flask.
- This cycle repeats continuously.
- Duration on Continue extraction for 6–8 hours.
- Approximately 10–15 siphon cycles are complete

Filtration:

- Pour the extracted solvent containing dissolved phytoconstituents into the funnel.

- Apply vacuum to facilitate rapid filtration.
- Ensure complete separation of liquid extract from insoluble residues



Fig no:11 filtration

Collection of Filtrate:

- Collect the clear filtrate in the receiving flask.
- If required, repeat filtration to ensure clarity

Hydroalcoholic Soxhlet Extraction of centella asiatica:

- Place powdered Centella asiatica in a Soxhlet apparatus.
- Use Hydroalcoholic as the extracting solvent.
- Heat gently so the solvent repeatedly passes through the plant material.
- Continue until adequate extraction is achieved.
- Filter and evaporate the solvent.
- Gives relatively exhaustive extraction.
- Useful for continuous extraction.

Principle:

A Soxhlet extractor works on the principle of continuous hot solvent extraction.
The solvent is heated to boiling, and its vapour condenses into the extraction chamber containing the powdered drug. When the solvent level reaches the siphon tube, it
automatically flows back into the flask carrying the extracted constituents. This cycle repeats continuously.

Procedure:

1. Weigh about 25–50 g of powdered drug.
2. Place the powder inside the Soxhlet thimble.
3. Add Hydroalcoholic to the round-bottom flask.
4. Assemble the Soxhlet apparatus with the condenser.

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5. Continue extraction for approximately 6–8 hours or
6. until the siphon solvent becomes nearly colorless.
7. Concentrate the extract using a rotary evaporator or gentle evaporation.
8. Store the concentrated extract in an airtight container at 2–8°C.



Fig no:12 Soxhlet extraction of Hydroalcoholic

Assembly:

- Connect the round bottom flask, Soxhlet extractor, and Condenser properly
- Ensure continuous water flow through the condenser.

Heating :

- Heat the system using a heating mantle.
- Maintain temperature at 60–65°C

Extraction Cycle:

- Solvent evaporates → condenses → fills extraction.
- When the chamber fills to siphon level, it automatically
- empties back into the flask.
- This cycle repeats continuously.
- Duration on Continue extraction for 6–8 hours
- Approximately 10-15 siphon cycles are complete

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Filtration:

- Pour the extracted solvent containing dissolved phytoconstituents into the funnel.
- Apply vacuum to facilitate rapid filtration.
- Ensure complete separation of liquid extract from insoluble residues



Fig no:13 filtration

Collection of Filtrate:

- Collect the clear filtrate in the receiving flask.
- If required, repeat filtration to ensure clarity

Phytochemical screening of Ethyl acetate:

1. Test for alkaloids:

The test solution was mixed with little amount of dil. HCl and Mayer's reagent formulation of a white P.P.T indicates the presence of alkaloids.[39]



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Fig no:14 Test for alkaloids

2. Test for Catechin:

Take 2ml of test solution, a few drops of Ehrlich reagent and concentrate HCL were added appearance of pink color indicates the presence of catechin.



Fig no:15 Test for catechin

3. Test for coumarin:

Take 2ml of test solution, a few drop of alcoholic sodium hydroxide were added appearance of yellow color indicates the presence of coumarin.[40]

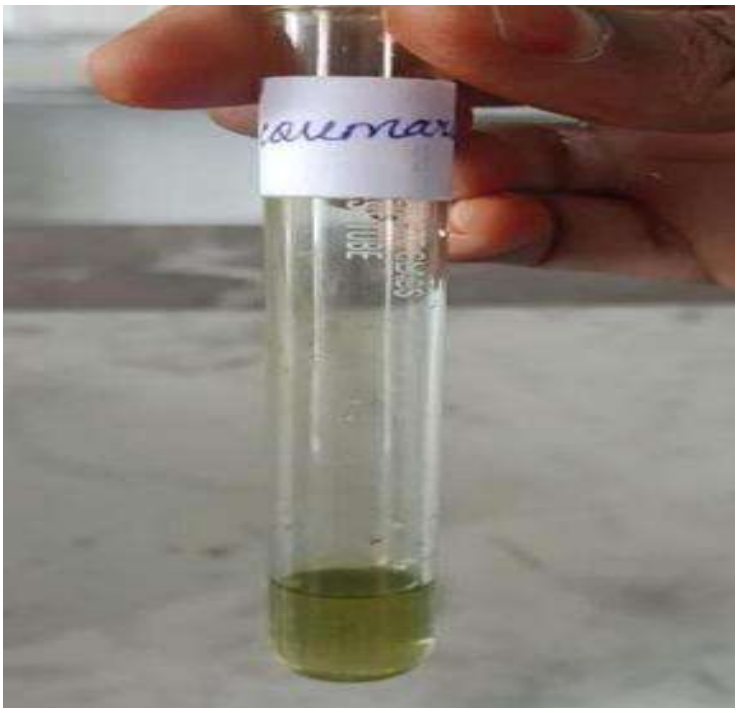


Fig no:16 Test for coumarin

4. Test for phenol:

Take 2ml of the test solution a few drops of (ferric chloride) solution were added bluish green or

red color indicator the presences of phenol.[41]



Fig no:17 Test for phenol

5. Test for saponin:

The test solution was shakes with water copious Lather formation indicates the presence of saponin.



Fig no:18 Test for saponin

6. Test for triterpenoid:

Add 1ml of extract 2ml of chloroform and addition of 2ml acetic anhydride with 2 drops of conc.H2SO4 from side of test tube then appearance of brown ring at junction and presence of blue-green color.[42]

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Fig no:19 Test for triterpenoid

7. Test for Salkowski test:

Add 1ml extract and 2ml of chloroform shake and add 2ml H2SO4 carefully to from a layer appearance of Reddish-brown colour at interface.[43]

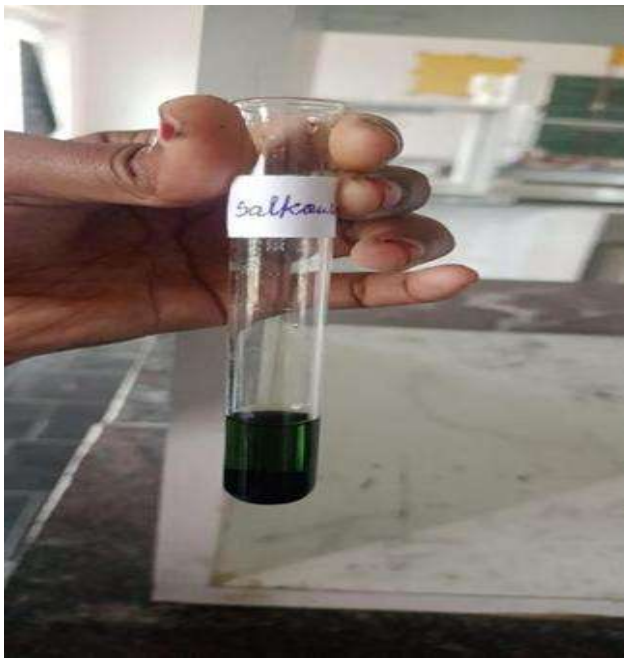


Fig no:20 Test for Salkowski test

8. Test for Lead acetate:

Add 1ml of extract and 3-4 drops of 10% lead acetate appearance of form of yellow colour.

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Fig no:21 Test of lead acetate

Phytochemical screening of Hydroalcoholic:

1. Test for alkaloids:

The test solution was mixed with little amount of dil. HCl and Mayer's reagent formulation of a white P.P.T indicates the presence of alkaloids.



Fig no:22 Test for alkaloids

2. Test for Catechin:

Take 2ml of test solution, a few drops of Ehrlich reagent and concentrate HCL were added appearance of pink color indicates the presence of catechin.[44]

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Fig no:23 Test of catechin

3. Test for coumarin:

Taking 2ml of test solution, a few drops of alcoholic sodium hydroxide were added appearance of yellow color indicates the presence of coumarin.



Fig no:24 Test of coumarin

4. Test for saponin:

The test solution was shaken with water copious Lather formation indicates the presence of saponin.[45]

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Fig no:25 Test of saponin

5. Test for phenol:

Taking 2ml of the test solution a few drops of (ferric chloride) solution were added bluish green or red color indicator the presences of phenol.



Fig no:26 Test of phenol

6. Test for triterpenoid:

Add 1ml of extract 2ml of chloroform and addition of 2ml acetic anhydride with 2 drops of conc.H2SO4 from side of test tube then appearance of brown ring at junction and presence of blue-green color.[46]

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Fig no:27 Test of Triterpenoid

7. Test for Salkowski test:

Add 1ml extract and 2ml of chloroform shake and add 2ml H2SO4 carefully to from a layer appearance of Reddish brown colour at interface.[47]



Fig no:28 Test of Salkowski

8. Test for Lead acetate:

Add 1ml of extract and 3-4 drops of 10% lead acetate appearance of form of yellow colour.[48]

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Fig no:29 Test of lead acetate

Antioxidant activity:

D.P.P.H Method: Principle:

The nitric oxide radical scavenging assay is based on the generation of nitric oxide (NO) from sodium nitroprusside in an aqueous solution. Nitric oxide reacts with oxygen to form nitrite ions, which react with Griess reagent to produce a pink-colored azo compound. Antioxidant compounds present in the test sample scavenge nitric oxide radicals and decrease the formation of the colored product. The decrease in absorbance is measured spectrophotometrically at 546 nm and is proportional to the nitric oxide scavenging activity of the sample.

Reagents:

The major reagents required are sodium nitroprusside (SNP), phosphate-buffered saline (PBS, pH 7.4), sulphadiazine, phosphoric acid, N-(1-naphthyl) ethylenediamine dihydrochloride (NED), methanol/distilled water or suitable solvent, and ascorbic acid as the standard antioxidant.

Procedure:

Different concentrations of the test extract are prepared, such as 20, 40, 60, 80 µg/ml. The test sample is mixed with sodium nitroprusside solution and incubated at room temperature in the dark for about 2.5 hours. After incubation, an aliquot of the reaction mixture is mixed with freshly prepared Griess reagent and allowed to stand for about 30 minutes at room temperature. The development of pink colour is measured at 546 nm using a UV-visible spectrophotometer. A control without the test extract and ascorbic acid as the standard are used for comparison. The percentage inhibition of nitric oxide is calculated to determine the antioxidant activity of the test sample.[49]

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D.P.P.H method of test ethyl acetate:

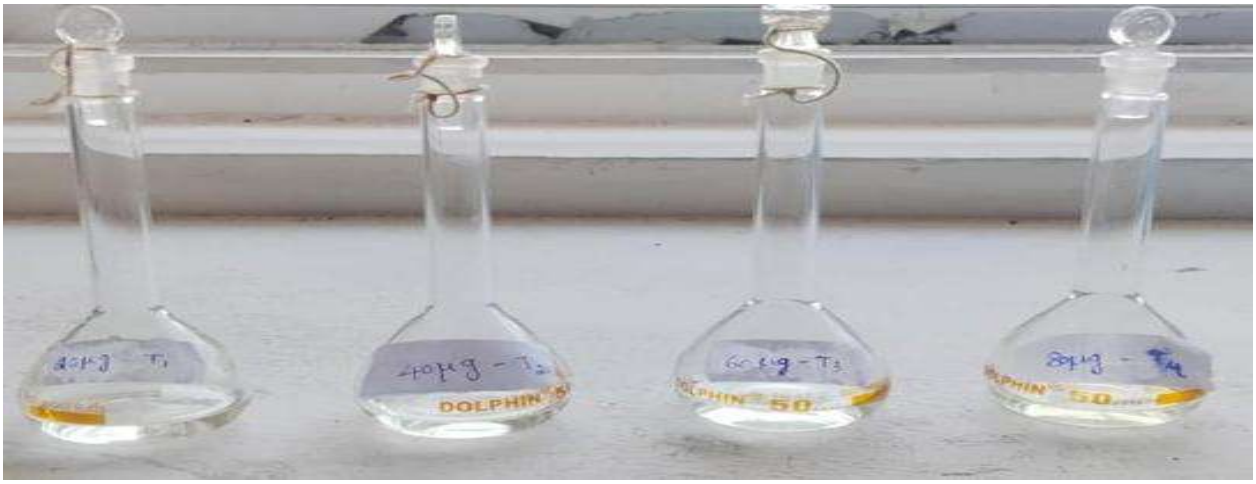


Fig no:30 D.P.P.H of test ethyl acetate

D.P.P.H method of test hydroalcoholic:



Fig no:31 D.P.P.H method of test hydroalcoholic

D.P.P.H method of standard ascorbic acid:



Fig no:32 D.P.P.H method of standard ascorbic acid

Anti inflammation activity:
Protocol for Free Radical Scavenging Assay (Nitric Oxide NO Assay):
Principle:
Nitric oxide (NO) is generated from sodium nitroprusside in an aqueous solution at physiological ph. It reacts with oxygen to produce nitrite ions (NO_2) which
Can be quantified using the Griess reagent. In the presence of antioxidants, nitric oxide is scavenged, leading to a decrease in nitrite formation. The reduction in absorbance at 546-550 nm reflects the NO scavenging ability of the compound.

Reagents:
Sodium nitroprusside (5 mM in PBS, pH 7.4)
Griess reagent (prepared fresh):
O 1% sulphanilamide in 5% phosphoric acid
O 0.1% N-(1-naphthyl) ethylenediamine dihydrochloride (NED) Phosphate buffer (0.1 M. pH 7.4)
Ascorbic acid (standard, 1 mg/ml)
Test sample (dissolved in DMSO/methanol/water)

Procedure:
1. Add 1 ml of sample or standard at different concentrations (e.g., 20-100 µg/ml).
2. Incubate the mixture at 25° C for 2.5 hours under light (to generate NO).
3. After incubation, take 1 ml of the reaction mixture and add 1 ml of Griess reagent.
4. Incubate for 30 minutes in the dark at room temperature.
5. Measure the absorbance at 546 nm using a UV-Vis Prepare 1 ml of 5 mM sodium nitroprusside in phosphate buffer.
6. spectrophotometer.[50]

D.P.P.H method of test ethyl acetate



Fig no:33 D.P.P.H of test ethyl acetate

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D.P.P.H method of test hydroalcoholic:

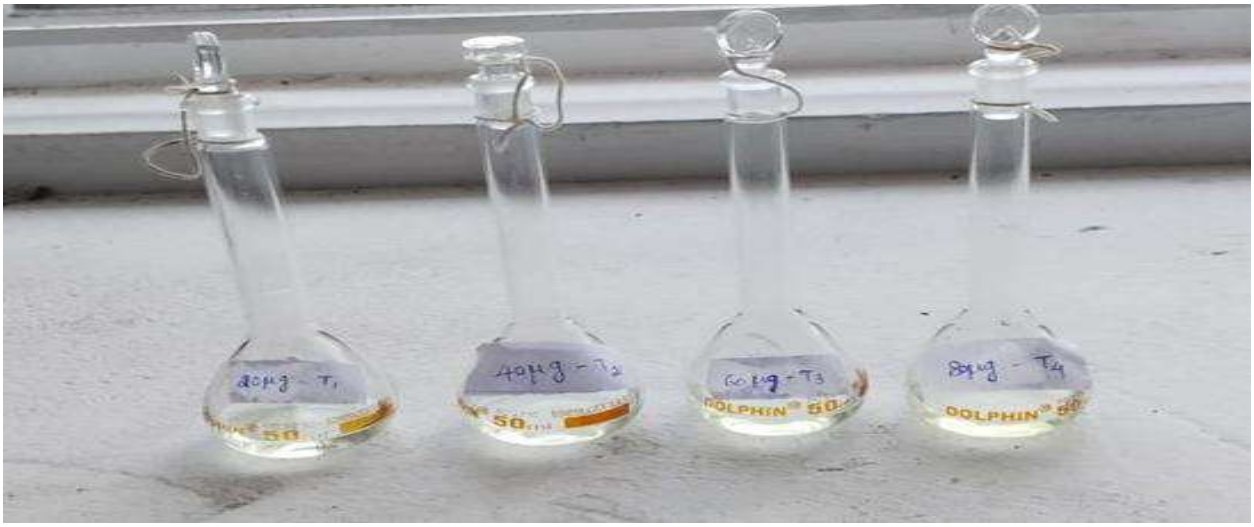


Fig no:34 D.P.P.H method of test hydroalcoholic

D.P.P.H method of standard ascorbic acid:



Fig no:35 D.P.P.H method of standard ascorbic acid

Result and conclusion:

Phytochemical Analysis:

The qualitative phytochemical screening results of the ethyl acetate extract (EAE) and hydroalcoholic extract (HAE) obtained from Centella asiatica leaves are presented.

Qualitative phytochemical analysis of EAE and HAE from Centella asiatica leaves

s.no	Phytoconstituent	Test performed	Ethyl acetate extract	Hydroalcoholic extract
1.	Alkaloids	Mayer's test	+	+
2.	Catechin	Ehrlich's test	_	_

3.	Coumarins	Alcoholic NaOH test	+	+
4.	Phenols	Ferric chloride test	+	+
5.	Saponins	Froth test	+	+
6.	Triterpenoids	Acetic anhydrous/H2SO4	+	+
7.	Glycosides	Salkowski test	+	+
8.	Tannins	Lead acetate test	+	+

+: Present (positive); - : absent (negative)

Table no: 6 Qualitative phytochemical analysis of EAE and HAE from Centella asiatica leaves

Both the ethyl acetate and hydroalcoholic extracts of Centella asiatica showed positive results for alkaloids, coumarins, phenols, saponins, triterpenoids, glycosides (Salkowski-positive), and tannins. However, the catechin test was negative in both extracts. The similar phytochemical profiles observed in the two extracts suggest that most of the major secondary-metabolite groups reported in this species (1,2,5) can be extracted over a relatively broad polarity range, extending from ethyl acetate to hydroalcoholic solvents. This finding agrees with earlier phytochemical investigations of C. asiatica, which have also described a diverse range of constituents (1,2,13). The lack of a positive catechin reaction in either extract is consistent with studies indicating that flavan-3-ol compounds, particularly catechin-type constituents, occur at relatively low or variable concentrations in C. asiatica compared with its major triterpenoid saponins and other phenolic compounds (1,2). Furthermore, the results demonstrate that a positive ferric chloride test for general "phenols" does not necessarily confirm the presence of every specific phenolic subclass.

Antioxidant activity – Nitric Oxide radical Scavenging Assay

The percentage inhibition of nitric oxide radical by the standard (ascorbic acid), the hydroalcoholic extract (HAE) and the ethyl acetate (EAE), at concentrations of 20,40,60 and 80ug/ml is presented in Table 4 .

Table 4: Percentage inhibition (NO radical scavenging assay – antioxidant evaluation)

Concentration (ug/ml)	Standard (Ascorbic Acid) %	HAF%	EAE%
20	72.41	81.40	58.74
40	73.52	78.81	60.96
60	73.27	68.22	61.33
80	73.02	68.84	61.82

Table no: 7 Antioxidant activity – Nitric Oxide radical Scavenging Assay

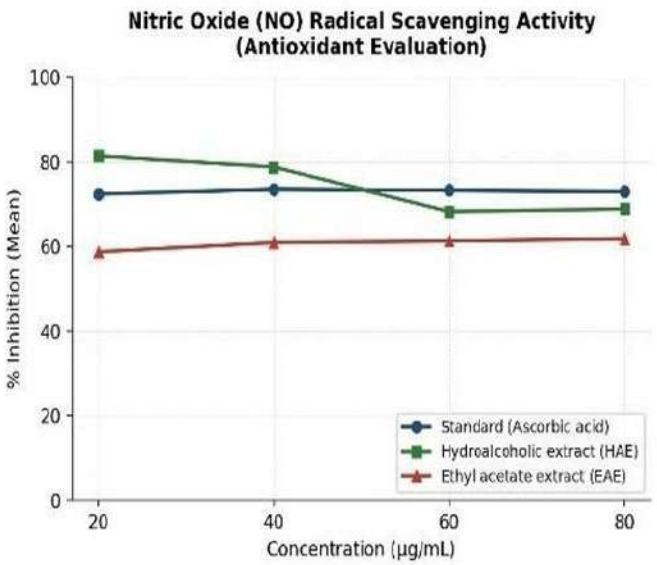


Fig. 6: Dose-response curve for nitric oxide radical scavenging (antioxidant) activity

Fig no: 36 Dose-response curve for nitric oxide radical scavenging (antioxidant) activity

The ascorbic acid standard product a relatively flat, near – maxim al inhibition profile across the tested range (72.42 -73.52%), consistent with reference antioxidant approaching saturation of the available nitric oxide radical even at the lowest concentration tested 981.40%at 20µg/ml),exceeding the standard, with a gradual decline to 68.22-68.84%at the two higher concentrations; this inverse concentration-activity pattern at the upper end of the tested range may reflect a degree of self-association or reduced solubility of the more polar hydroalcoholic constituents at higher loading, a phenomenon occasionally reported for polyphenol- rich plant extract in radical-scavenging assays (19,42) the ethyl acetate extract, in contract, displayed a conventional concentration-dependent increase in activity, rising steadily from 58.74% at 20ug/ml to 61.82% at 80ug/ml, though its overall inhibition remained lower than that of both the standard and the hydroalcoholic extract across the tested range. Because percentage inhibition for all three test articles exceeded 50% already at the lowest concentration examined (20ug/ml), the concentration range used in this study did not bracket the turn IC50 of the standard or of either extract, and a reliable interpolated IC50 of standard of either extract and a reliable interpolated IC50 value could not be calculated from the present data; wider ,lower concentration dilution series (for example,1-20ug/ml) would be required in follow-up work to determine IC50 value with confidence. Taken together, these results indicate that the hydroalcoholic extract of asiatic contains a higher concentration of nitric-oxide-scavenging and by extension anti-oxidant phytoconstituents-most plausibly phenolics and flavonoid glycosides that partition preferentially into the more polar hydroalcoholic solvent system-than the ethyl acetate extract, a pattern that parallels previous reports of solvent-polarity-dependent antioxidant activity in this species(42) and in other medicinal plants(48,50).

Anti-inflammatory activity -Griess-based nitric oxide scavenging assay:

The percentage inhibition of nitric oxide, used as a surrogate measure of Anti-inflammatory potential, for the standard, HAE and EAE at concentration of 20,40,60 and 80 ug/ml is presented in table 5 and fig.

Table 5: percentage inhibition (Griess-based NO scavenging assay-inflammatory evaluation)

Concentration(ug/ml)	ndard (Ascorbic acid)%	HAE%	EAE%
20	55.47	57.38	20.92
40	55.27	55.66	18.80
60	53.55	57.00	17.08
80	51.82	56.62	15.35

Table no:8percentage inhibition (Griess-based NO scavenging assay- inflammatory evaluation)

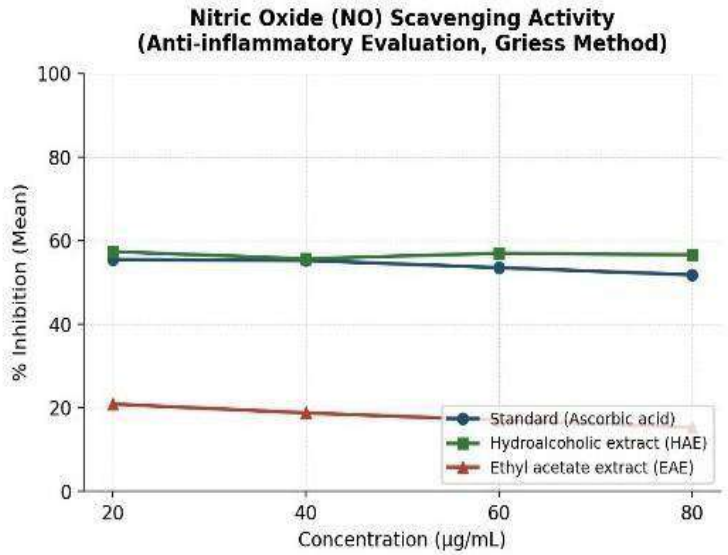


Fig. 7: Dose-response curve for Griess-based nitric oxide scavenging (anti-inflammatory) activity

Fig no:37 Dose-response curve for Griess-based nitric oxide scavenging (anti-inflammatory) activity

The standard ascorbic acid showed a modest, gradual decline in NO inhibition with increasing concentration (55.47% to 51.82%) remaining above 50% throughout the tested range. The hydroalcoholic extract maintained a consistently high and comparatively stable level of NO scavenging across all four concentrations marginally exceeding the standard. This is consistent with the anti-inflammatory activity reported for polar centella asiatica extract and fractions in macrophage-based NO/iNOS suppression assays system (24.31.32), and support the interpretations that the phenolic and saponin-rich hydroalcoholic fraction retains meaningful anti-inflammatory potential in this assays system. The ethyl acetate extract by contract, showed distinctly weaker activity that declined progressively with increased concentration, from 20.92% at 20ug/ml

to 15.38% at 80ug/ml because EAE remained below 50% inhibition across the entire tested range. Its NO scavenging (anti-inflammatory) IC50 could not be determined from the present data and would require testing at concentration beyond 80ug/ml.

The markedly weaker and inversely concentration-related anti-inflammatory activity of the ethyl acetate extract, relative to its comparatively stronger and concentration-dependent performance in the antioxidant assay (section 7.2). suggests that the phytoconstituent responsible for direct free-radical scavenging in EAE are not equally effective at intercepting inflammatory nitric oxide generation.

III. STANDARD ASCORBIC ACID

S.NO	CONTROL	20ug	40ug	60ug	80ug
1	0.811	0.224	0.215	0.216	0.221
2	0.813	0.223	0.215	0.217	0.219
3	0.812	0.224	0.216	0.217	0.218
AVG	0.812	0.224	0.215	0.217	0.219
%	-	72.41	73.52	73.27	73.02

Table no:9 standard ascorbic acid

IV. TEST SAMPLE (HYDROALCOHOL)

S.NO	CONTROL	20ug	40ug	60ug	80ug
1	0.811	0.151	0.173	0.253	0.252
2	0.813	0.153	0.171	0.258	0.256
3	0.812	0.151	0.172	0.258	0.252
AVG	0.812	0.515	0.172	0.258	0.253
%		81.40	78.81	68.22	68.84

Table no:10 test sample hydroalcoholic

V. TEST SAMPLE (ETHYL ACETATE)

S.NO	CONTROL	20ug	40ug	60ug	80ug
1	0.811	0.337	0.317	0.317	0.310
2	0.813	0.335	0.311	0.314	0.310
3	0.812	0.334	0.223	0.312	0.311
AVG	0.812	0.335	0.317	0.312	0.310
%		58.74	60.96	61.33	61.82

Table no:11 test sample ethyl acetate

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Standard Ascorbic Acid:

CONCENTRATION	0D1	0D2	0D3	MeanOD	%
CONTROL	0.521	0.521	0.523	0.521	
20ug	0.231	0.232	0.234	0.232	55.47
40ug	0.232	0.233	0.234	0.233	55.27
60ug	0.241	0.242	0.243	0.242	53.55
80ug	0.251	0.253	0.251	0.251	51.82

Table no:12 standard ascorbic acid

VI. TEST SAMPLE (HYDROALCOHOL)

CONCENTRATION	OD1	OD2	OD3	MEAN OD	%
CONTROL	0.521	0.521	0.523	0.521	
20ug	0.222	0.221	0.223	0.222	57.38
40ug	0.231	0.231	0.231	0.231	55.66
60ug	0.224	0.225	0.224	0.224	57.00
80ug	0.226	0.226	0.227	0.226	56.62

Table no:13 test sample hydroalcoholic

VII. TEST SAMPLE (ETHYL ACETATE)

CONCENTRACTION	OD1	OD2	OD3	MEANOD	%
CONTROL	0.521	0.521	0.523	0.521	
20ug	0.412	0.413	0.412	0.412	20.92
40ug	0.423	0.423	0.424	0.423	18.80
60ug	0.431	0.432	0.433	0.432	17.08
80ug	0.441	0.442	0.441	0.441	15.35

Table no:14 test sample ethyl acetate

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Adansonia digitata L A Review of Its Nutritional, Phytochemical, Antioxidant, Antimicrobial and Hepatoprotective Potential

Chetana Lahariya
Assistant Professor: Priyadarshini J. L. College of Pharmacy, Nagpur

***Abstract*—Adansonia digitata L., commonly known as baobab, is a multipurpose tree belonging to the family Malvaceae and is widely valued for its nutritional, traditional, and medicinal applications. Different parts of the plant, including the leaves, stem bark, roots, flowers, seeds, and fruit pulp, have been traditionally used as food and remedies for a variety of health conditions. The available evidence summarized in the present review indicates that A. digitata contains several classes of bioactive phytochemicals, including alkaloids, saponins, flavonoids, tannins, terpenoids, steroids, and glycosides. The fruit pulp is particularly notable for its vitamin C content, dietary fibre, and antioxidant potential. Experimental investigations have reported antioxidant, antimicrobial, amoebicidal, and hepatoprotective activities associated with different plant parts and extracts. Ethanolic leaf extract demonstrated amoebicidal activity against Entamoeba histolytica, while extracts of the leaves and stem bark exhibited antibacterial activity against bacterial isolates including Escherichia coli and Salmonella typhi. The plant also demonstrated free-radical-scavenging activity in the DPPH assay, although the activity varied according to plant part and extract. In an experimental model of carbon tetrachloride-induced hepatotoxicity, methanolic fruit-pulp extract showed hepatoprotective potential. Collectively, these findings support the potential of A. digitata as a source of nutritional and biologically active compounds. However, variations in extraction procedures, plant parts, experimental models, and reported outcomes highlight the need for standardized phytochemical characterization, toxicity assessment, mechanistic investigations, and well-designed controlled studies before therapeutic applications can be established.**

***Index Terms*—Adansonia digitata; baobab; phytochemicals; antioxidant activity; antimicrobial activity; amoebicidal activity; hepatoprotection; fruit pulp; medicinal plants; nutritional value.**

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I. INTRODUCTION

Adansonia digitata L., commonly known as the baobab tree, belongs to the family Malvaceae and is the most widespread species of the genus Adansonia. The species has considerable nutritional, cultural, and medicinal importance. Different parts of the plant have traditionally been used as food as well as in folk medicine.

The leaves are nutritionally important and have been described as a source of protein that can complement the amino-acid profile of the diet. Young leaves are commonly consumed as vegetables, while dried leaves may be incorporated into soups throughout the year. Flowers may also be consumed or used as flavouring materials in drinks. The fruit pulp has attracted particular attention because of its nutritional composition and antioxidant properties.

Traditional medicinal applications of A. digitata include the management of fever, diarrhoea, malaria, haemoptysis, dysentery, and conditions associated with vitamin C deficiency. Various preparations of the stem bark, root bark, leaves, and fruit pulp have also been used traditionally. The diversity of traditional applications has stimulated investigations into the phytochemical composition and biological activities of the plant.

The available experimental evidence summarized in the source material indicates that A. digitata possesses several potentially beneficial biological properties, including antioxidant, antimicrobial, amoebicidal, and hepatoprotective effects. The objective of this review is to organize the available information concerning the nutritional importance, phytochemical constituents, biological activities, and medicinal potential of A. digitata, while identifying important areas for further investigation.



II. BOTANICAL AND ETHNOMEDICINAL IMPORTANCE

The baobab is described as a multipurpose tree whose different organs have nutritional and medicinal uses. Leaves are consumed as vegetables or dried for later incorporation into traditional foods. Flowers can be eaten or incorporated into beverages. Bark preparations have been used traditionally for medicinal purposes, and a semi-fluid gum obtained from the bark has been reported as a traditional treatment for sores.

The stem bark has historically received considerable attention in traditional medicine. Bark preparations have been described as decoctions used internally, with their activity associated in part with soluble and insoluble tannins and gummy and albuminous constituents. β-Sitosterol has also been reported from bark and seed oil. Root bark has similarly been used in traditional medicine and has been reported to contain β-sitosterol and glycosides.

The leaves and roots have also been incorporated into traditional remedies, including preparations used as tonics for individuals affected by malaria. These applications provide a basis for investigating the chemical constituents and biological activities of different parts of the plant.

III. NUTRITIONAL IMPORTANCE OF ADANSONIA DIGITATA

The fruit pulp of A. digitata is an important nutritional component of the plant. The available material characterizes the pulp as having a high vitamin C content and substantial antioxidant capacity. It is also described as containing a high proportion of carbohydrates, relatively low protein, extremely low fat, and high crude fibre.

The high fibre content may have physiological and homoeostatic benefits for the intestine and colon. Consequently, the fruit pulp has been considered a potentially useful dietary supplement.

The leaves also have nutritional relevance. Their protein content can contribute to the overall amino-acid profile of diets in which they are consumed with other staple foods. This is particularly relevant in traditional dietary systems where dried leaves are incorporated into staple meals.

IV. PHYTOCHEMICAL CONSTITUENTS

Phytochemical screening of A. digitata leaf and stem-bark extracts has demonstrated the presence of several classes of secondary metabolites. The reported constituents include alkaloids, saponins, flavonoids, steroids, tannins, and terpenoids. Additional screening procedures investigated glycosides, resins, anthraquinones, proteins, and amino acids.

The detection of these phytochemical classes provides a possible chemical basis for some of the biological activities reported for the plant. For example, phenolic-associated constituents such as tannins and flavonoids are relevant to antioxidant investigations, whereas several classes of secondary metabolites may contribute to antimicrobial effects.

However, preliminary phytochemical screening provides qualitative evidence of constituent classes rather than definitive identification or quantification of individual compounds. Therefore,

further chromatographic and spectrometric characterization is necessary to establish the chemical profile of A. digitata extracts.

V. ANTIOXIDANT ACTIVITY

Oxidative stress is associated with cellular damage and has been implicated in numerous pathological processes. Because of this, antioxidant properties of medicinal plants have attracted considerable research attention.

The antioxidant potential of A. digitata extracts has been assessed using the DPPH radical-scavenging assay and an iron-chelating assay. In the DPPH assay, the extract of A. digitata leaves showed relatively low radical-scavenging activity, with a reported value of approximately 13 ± 0.03% radical-scavenging activity. In comparison, Cucurbita maxima seed extract showed moderate activity of approximately 38 ± 0.02%.

The iron-chelating assay did not demonstrate activity for the investigated extracts. These observations indicate that antioxidant activity may vary substantially according to plant part, extraction procedure, and assay system.

The antioxidant properties of the fruit pulp have also been emphasized in the source material, particularly in association with its high vitamin C content. The reported antioxidant capacity provides a possible explanation for some of the protective effects observed in experimental models.

VI. ANTIMICROBIAL ACTIVITY

The antimicrobial potential of A. digitata has been investigated using different extracts and experimental methods. Leaf and stem-bark extracts prepared using aqueous, ethanol, and chloroform-based extraction procedures were assessed against bacterial isolates.

The reported bacterial isolates included Escherichia coli and Salmonella typhi. Preliminary phytochemical screening demonstrated the presence of several bioactive constituent classes in the investigated plant materials.

The antibacterial activity was assessed using agar well or cup-plate diffusion methods. Extract concentrations were tested and inhibition zones were measured after incubation. In another experimental investigation, ethanolic leaf extract was evaluated against standard bacterial strains including E. coli, Pseudomonas aeruginosa, Bacillus subtilis, and Staphylococcus aureus. Fungal organisms including Candida albicans and Aspergillus niger were also included.

Minimum inhibitory concentration (MIC) was determined using dilution-based methods. The available findings indicate that aqueous, ethanol, and chloroform extracts of A. digitata leaves and stem bark were capable of inhibiting the growth of the tested bacterial isolates, with inhibition reported at higher concentrations, including 40 mg/mL.

These findings suggest that A. digitata contains compounds with antimicrobial potential. Nevertheless, differences in extraction procedures and experimental conditions make direct comparison between studies difficult.

VII. AMOEBICIDAL ACTIVITY

The source material also reports investigation of the amoebicidal activity of medicinal plant extracts against Entamoeba histolytica. Ethanolic A. digitata leaf extract was tested using an in-vitro susceptibility assay.

The ethanolic leaf extract demonstrated 100% inhibition after 96 hours at concentrations of 500 and 250 ppm. Under the same experimental conditions, metronidazole, which was used as the reference control, produced approximately 80% mortality.

These findings provide preliminary evidence that A. digitata leaf extract may possess amoebicidal activity. However, the results are derived from an in-vitro experimental model and should not be interpreted as evidence of clinical efficacy. Additional investigations are required to identify the active compounds, determine their mechanism of action, establish dose-response relationships, and evaluate safety.

VIII. HEPATOPROTECTIVE POTENTIAL

The liver is particularly susceptible to chemical and oxidative injury. The hepatoprotective properties of A. digitata fruit pulp have been investigated using an experimental model of carbon tetrachloride (CCl_4)-induced hepatotoxicity in rats.

In the reported experimental design, rats were divided into normal-control, negative-control, standard-control, and treatment groups. Hepatotoxicity was induced using CCl_4. Silymarin was used as a standard treatment, while methanolic A. digitata extract was administered at doses of 100 and 200 mg/kg/day. Treatment was continued for 21 days, with CCl_4 administered at 72-hour intervals.

The reported findings indicate that oral administration of A. digitata fruit-pulp methanolic extract exhibited hepatoprotective properties in the CCl_4-induced model. The protective effect was suggested to be associated with the antioxidant capacity of the extract.

These observations are promising but remain preclinical. The available material itself recommends further evaluation of efficacy and safety using well-designed controlled studies.

IX. RELATIONSHIP BETWEEN PHYTOCHEMICALS AND BIOLOGICAL ACTIVITY

The biological effects reported for A. digitata may be associated with the presence of multiple classes of secondary metabolites and nutritional constituents. The detection of flavonoids, tannins, terpenoids, alkaloids, saponins, and steroids suggests that the plant contains a chemically diverse mixture of bioactive constituents.

The antioxidant potential may be related to antioxidant-associated constituents and the high vitamin C content of the fruit pulp. Antimicrobial activity may similarly result from interactions among several secondary metabolites rather than a single compound.

The hepatoprotective effects observed experimentally may also be related to the antioxidant capacity of the fruit-pulp extract. However, the source material does not establish specific molecular mechanisms or identify individual compounds responsible for these activities. Such relationships should therefore be regarded as potential explanations requiring experimental confirmation.

X. LIMITATIONS OF THE AVAILABLE EVIDENCE

Although the reported findings indicate considerable biological potential, several limitations should be considered.

First, different studies have investigated different plant parts, including leaves, stem bark, and fruit pulp. Biological activity cannot therefore be generalized uniformly to the entire plant.

Second, extraction procedures differed substantially among investigations, including aqueous, ethanol, methanol, and chloroform extraction. Differences in solvent polarity, extraction duration, temperature, and concentration can influence the chemical composition and biological activity of the resulting extracts.

Third, several investigations used preliminary phytochemical screening rather than quantitative chemical characterization. Consequently, the exact concentrations and identities of many potentially active compounds remain unclear.

Fourth, several reported biological activities were demonstrated in vitro or in animal models. Such results provide preliminary evidence but cannot by themselves establish efficacy or safety in humans.

Finally, the available source material contains references in abbreviated or incomplete form. Comprehensive bibliographic verification will therefore be necessary before submission to an SCI-indexed journal.

XI. FUTURE RESEARCH PERSPECTIVES

Future investigations should focus on systematic chemical characterization of A. digitata extracts and isolation of the compounds responsible for the observed biological activities. Standardized extraction procedures should be established to facilitate comparison between studies.

Quantitative determination of phenolics, flavonoids, vitamin C, and other relevant constituents would strengthen the relationship between chemical composition and biological activity. Mechanistic studies should also be conducted to clarify how individual extracts or compounds produce antioxidant, antimicrobial, amoebicidal, and hepatoprotective effects.

Toxicological studies are particularly important before therapeutic applications can be considered. The hepatoprotective findings reported in animal models should be investigated using standardized biochemical, histopathological, and molecular endpoints.

Finally, well-designed controlled studies are required to determine whether the promising preclinical findings can translate into meaningful health benefits in humans.

XII. CONCLUSIONS

Adansonia digitata L. is a nutritionally and medicinally important multipurpose tree with considerable potential as a source of bioactive and dietary constituents. The available evidence indicates the presence of several phytochemical classes, including alkaloids, saponins, flavonoids, tannins, terpenoids, and steroids.

The fruit pulp is particularly notable for its vitamin C content, antioxidant potential, carbohydrate content, and high dietary fibre. Experimental studies summarized in the present review indicate antioxidant, antibacterial, amoebicidal, and hepatoprotective activities associated with different parts and extracts of the plant.

However, the existing evidence remains heterogeneous, and much of the reported activity is based on preliminary in-vitro or animal studies. Standardized extraction, detailed phytochemical characterization, toxicological evaluation, mechanistic studies, and controlled clinical investigations are required to establish the therapeutic significance of A. digitata. Thus, while the plant represents a promising nutritional and pharmacological resource, its medicinal applications require further scientific validation.

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Digital Tools and Technologies in Enhancing English Literacy a Systematic Literature Review

A K Deepa Prem
Associate Professor, SKP Arts and Science College, Tiruvannamalai, Tamilnadu

***Abstract*—The rapid expansion of digital technology has reshaped how English literacy and language skills are taught and acquired around the world. This paper presents a systematic literature review examining how digital tools and technologies contribute to English literacy development, drawing on peer-reviewed studies published between 2020 and 2023. The review synthesizes findings across four thematic areas: conceptual foundations of digital literacy in language education, teachers' perceptions and adoption of digital tools, the role of mobile-assisted language learning (MALL) in vocabulary and skill development, and the persistent challenges that hinder digital integration in English as a Foreign Language (EFL) and English as a Second Language (ESL) classrooms. The findings indicate that digital tools, ranging from mobile applications and digital flashcards to multimedia and web-based platforms, can meaningfully support reading, writing, and vocabulary development when supported by adequate teacher training, institutional support, and pedagogically sound implementation. However, barriers such as limited digital competence among teachers, inconsistent access to infrastructure, and insufficient policy guidance continue to constrain widespread and equitable adoption. The paper concludes by outlining pedagogical implications and proposing directions for future empirical research, particularly longitudinal and comparative studies that examine the sustained impact of digital tools on English literacy outcomes across diverse educational contexts.**

***Index Terms*—digital literacy; English language teaching; mobile-assisted language learning; educational technology; literacy development**

I. INTRODUCTION

English continues to function as a global lingua franca, and proficiency in English literacy, encompassing reading, writing, vocabulary, and communicative competence, remains a central goal of language education systems worldwide. Over the past decade, the proliferation of digital technology has fundamentally altered the tools available to language learners and educators. Mobile applications, digital flashcards, multimedia platforms, and web-based resources are now

routinely embedded in English language classrooms, prompting scholars to examine whether and how these tools genuinely enhance literacy outcomes.

Traditional approaches to English literacy instruction, which often rely heavily on printed textbooks and teacher-centered delivery, have been criticized for struggling to sustain learner engagement in an era where students are accustomed to interactive, on-demand digital content. Educational technology promises several potential advantages: personalized pacing, immediate feedback, multimodal input, and opportunities for learning beyond the physical classroom. At the same time, the integration of digital tools introduces new demands on teachers' digital competence, institutional infrastructure, and curriculum design.

Given the volume of recent empirical work on this topic, a synthesis of the literature is warranted to clarify what is currently known about the relationship between digital tools and English literacy development, and to identify gaps that merit further investigation. This paper addresses three guiding questions: (1) How is digital literacy conceptualized within English language education research? (2) What does the literature reveal about the effectiveness of specific digital tools, particularly mobile-assisted language learning, in supporting reading, writing, and vocabulary development? and (3) What challenges and barriers do teachers and institutions face when integrating digital tools into English literacy instruction? By addressing these questions, this review aims to provide a coherent, evidence-based foundation for both researchers and practitioners seeking to make informed decisions about digital tool adoption in English language classrooms.

II. LITERATURE REVIEW

2.1 Conceptualizing Digital Literacy in Language Education

Digital literacy in language education is generally understood as the combination of technical skill and pedagogical judgment needed to select, use, and evaluate digital resources for teaching and learning purposes. Nguyen and Habók (2023) conducted a systematic review of instruments used to assess teacher digital literacy, synthesizing thirty-three peer-reviewed studies indexed in ERIC, Web of Science, and Scopus between 2011 and 2022. Their review found that most existing instruments concentrate on teachers' use of educational technology for instructional delivery, professional development, and learner support, but that comparatively little attention has been paid to validating these instruments across different subject areas, including English language teaching specifically.

This gap is notable because digital literacy is not a generic, transferable skill; the competencies required to use a grammar-checking application effectively differ from those needed to design a multimedia reading lesson or moderate an online discussion forum. Nguyen and Habók (2023) further observed that the majority of reviewed studies focus on assessing digital literacy among students rather than teachers, despite teachers being the primary agents responsible for translating digital tools into meaningful classroom practice. This asymmetry in the literature underscores the

need for research that specifically examines English language teachers' digital competence and how it shapes their instructional choices.

2.2 Teachers' Perspectives on Digital Tool Integration

Teachers' attitudes and beliefs play a decisive role in whether digital tools are adopted meaningfully in the classroom or used only superficially. Sim and Ismail (2023) conducted a systematic literature review, following the PRISMA framework, of twenty-four empirical studies drawn from Scopus and Web of Science examining English language teachers' perceptions of digital tools between 2019 and 2023. Their synthesis found that the majority of teachers held generally positive views toward digital tool integration, and identified several converging factors that shaped these perceptions: teachers' computer readiness and prior experience with technology, the quality and availability of institutional training and support, individual attitudes toward pedagogical innovation, and teachers' perceptions of the specific benefits and drawbacks associated with particular tools.

Notably, Sim and Ismail (2023) reported that teachers with stronger digital literacy skills tended to hold more favorable perceptions of digital tools, suggesting a reciprocal relationship between competence and attitude: greater familiarity with technology appears to build confidence, which in turn encourages further experimentation and adoption. Tools such as chatbots and augmented reality applications were viewed positively when teachers perceived clear pedagogical benefits, such as improved learner engagement, autonomy, and opportunities for immediate feedback, even among teachers who were initially unfamiliar with such technologies. This pattern indicates that perceived usefulness, rather than novelty alone, is a key driver of sustained digital tool adoption in English language classrooms.

2.3 Mobile-Assisted Language Learning and Vocabulary Development

Among the various categories of educational technology, mobile-assisted language learning (MALL) has attracted substantial empirical attention, particularly in relation to vocabulary acquisition, which is widely regarded as foundational to broader reading, writing, speaking, and listening competence. Lei, Fathi, Noorbakhsh, and Rahimi (2022) conducted a year-long quantitative longitudinal study examining the impact of a MALL program on 139 EFL learners' vocabulary learning attitudes and self-regulatory capacity. Using latent growth curve modelling, the researchers found that both learners' attitudes toward vocabulary learning and their capacity for self-regulated learning improved significantly over the course of the intervention, and that changes in these two variables were positively correlated with one another.

This finding is significant because it suggests that the benefits of MALL extend beyond immediate test-score gains to encompass more durable motivational and self-regulatory changes, which may sustain learners' engagement with English vocabulary study even after a specific program or application is no longer in use. Other studies in this domain have examined the integration of multiple mobile applications, such as flashcard tools, quiz platforms, and messaging applications, into formal instruction, generally reporting favorable effects on vocabulary retention, though the

magnitude of improvement varies depending on the specific application, the duration of the intervention, and the degree to which mobile activities are integrated with, rather than merely supplementary to, classroom instruction.

2.4 Digital Tools for Reading and Writing Skill Development

Beyond vocabulary acquisition, digital tools have also been examined for their contribution to reading and writing skill development more broadly. Joseph and Khan (2020) conducted a detailed literature review synthesizing sixty research articles from multiple countries, including Pakistan, Malaysia, China, Indonesia, and the United Kingdom, examining how digital literacy tools such as tablets, digital audiobooks, interactive whiteboards, and multimedia resources contribute to English reading and writing skills. Their review organized findings around five thematic areas, encompassing reading skill development, writing skill development, the Technological Pedagogical Content Knowledge (TPACK) teaching model, socially shared cognition theory, and research methodology trends within the field.

Joseph and Khan (2020) reported that digital tools were most consistently associated with gains in vocabulary knowledge, phonemic awareness, reading comprehension, and reading fluency, while writing-related benefits were most evident in areas such as grammar accuracy, sentence construction, and paragraph organization. Importantly, their review emphasized that digital tools appeared to be most effective when embedded within a coherent pedagogical framework, such as TPACK, rather than used as isolated add-ons to existing instruction. This finding aligns with the broader literature suggesting that technology alone does not drive literacy gains; rather, it is the interaction between well-designed digital resources and sound pedagogical scaffolding that produces measurable improvements in learner outcomes.

2.5 Barriers and Challenges to Digital Integration

Despite generally positive findings regarding the potential of digital tools, the literature consistently identifies substantial barriers to their effective and equitable implementation. Sim and Ismail (2023) categorized these challenges into several recurring themes: insufficient teacher training and technical knowledge, unreliable infrastructure such as poor internet connectivity and inadequate hardware, limited institutional support and unclear policy guidance, time constraints that leave teachers with little opportunity to develop new digital competencies, and variability in students' own digital literacy and engagement levels.

These challenges are not evenly distributed; several of the reviewed studies noted that teachers in under-resourced or rural settings faced compounded difficulties, including limited access to devices and a lack of localized training programs tailored to their specific classroom contexts. Nguyen and Habók (2023) similarly noted that the tools available for assessing digital literacy remain unevenly developed and validated across different educational and cultural contexts, which complicates efforts to design targeted interventions or professional development programs. Taken together, these findings suggest that the barriers to digital integration in English literacy instruction

are not primarily technological in nature, but rather structural and institutional, relating to training, support, and policy rather than the inherent limitations of the tools themselves.

III. DISCUSSION

Synthesizing across the reviewed studies, several patterns emerge. First, digital tools appear to offer genuine pedagogical value for English literacy development, particularly in vocabulary acquisition and reading skill development, but this value is contingent on thoughtful implementation rather than technology adoption for its own sake. Second, teacher digital competence and attitude function as critical mediating variables: tools that are perceived as pedagogically useful and that are supported by adequate training tend to be adopted more readily and used more effectively, whereas tools introduced without corresponding professional development risk superficial or inconsistent use.

Third, the literature reveals a persistent tension between the promise of digital tools and the structural realities of many educational contexts, particularly in developing regions where infrastructure, institutional support, and training opportunities remain uneven. This tension suggests that future research and policy efforts should focus less on identifying new digital tools and more on addressing the systemic conditions, such as sustained teacher training, equitable infrastructure investment, and clear institutional guidelines that determine whether existing tools can be used effectively. Finally, the relatively short duration of many of the reviewed studies, with the notable exception of Lei et al.'s (2022) year-long design, limits the field's understanding of whether early gains in vocabulary, reading, or writing are sustained over time, underscoring the need for more longitudinal research.

IV. PEDAGOGICAL IMPLICATIONS

The findings of this review carry several practical implications for English language educators, teacher trainers, and policymakers. First, teacher professional development programs should move beyond generic digital literacy training toward subject-specific applications, equipping English teachers with the skills to select and adapt digital tools for reading, writing, and vocabulary instruction specifically, rather than treating digital competence as a one-size-fits-all skill set. Second, institutions should prioritize embedding digital tools within established pedagogical frameworks, such as TPACK, rather than introducing them as standalone supplements, since the reviewed evidence suggests that pedagogically integrated tools produce more consistent literacy gains than isolated technology use.

Third, given the demonstrated benefits of mobile-assisted language learning for vocabulary development and learner self-regulation, curriculum designers might consider structured, sustained MALL programs, delivered over months rather than weeks, to maximize both cognitive and motivational benefits. Finally, addressing structural barriers, particularly infrastructure gaps and inconsistent institutional support, should be treated as a policy priority alongside teacher

training, since even highly competent and motivated teachers cannot implement digital tools effectively without adequate technical and administrative support.

V. CONCLUSION

This literature review has examined how digital tools and technologies contribute to English literacy development, drawing on recent systematic reviews and empirical studies spanning teacher perceptions, mobile-assisted language learning, and reading and writing skill development. The synthesized evidence indicates that digital tools hold considerable promise for enhancing English literacy outcomes, particularly when their use is grounded in sound pedagogical frameworks and supported by adequate teacher training and institutional infrastructure. At the same time, persistent structural barriers, including uneven access to training, technology, and support, continue to constrain the equitable realization of this promise across diverse educational contexts.

Future research would benefit from longitudinal designs that track literacy outcomes over extended periods, comparative studies examining digital tool effectiveness across different learner populations and educational settings, and investigations into the specific conditions under which teacher training translates into sustained, pedagogically sound digital tool use. As digital technologies continue to evolve, ongoing empirical attention to their role in English literacy education will remain essential for ensuring that innovation translates into meaningful and equitable learning gains.

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An Enhanced Intrusion Detection System using Hybrid CNN-LSTM Architecture

Jayesh Mahawer

Sage University Indore

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***Abstract*—The rapid proliferation of the Internet of Things (IoT) and Industrial Internet of Things (IIoT) has revolutionized digital infrastructure but introduced a vast attack surface for sophisticated cyber threats. Traditional Intrusion Detection Systems (IDS), which rely on signature-based matching and manual feature engineering, are increasingly fragile against zero-day exploits and polymorphic malware. This review paper examines the shift toward hybrid deep learning architectures, specifically the integration of Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) networks. By synergistically capturing both spatial intra-flow patterns and long-term temporal dependencies, these hybrid frameworks bridge the semantic gap between raw network telemetry and high-level threat identification, achieving state-of-the-art results across modern benchmark datasets.**

I. INTRODUCTION

Contextualizing Industrial IoT (IIoT) Security

The Industrial Internet of Things (IIoT) represents a paradigm shift in industrial operations, facilitating large-scale device connectivity, real-time telemetry, and sophisticated automated control systems. While these advancements significantly enhance operational efficiency and device performance, they simultaneously expand the attack surface for cyber adversaries. IIoT environments are increasingly susceptible to catastrophic threats, including Denial-of-Service (DoS), Distributed Denial-of-Service (DDoS), ransomware, and unauthorized lateral movement within industrial control networks.

The Necessity of Advanced IDS

Traditional perimeter defenses, such as legacy firewalls and signature-based antivirus solutions, lack the granularity required to identify the polymorphic nature of modern IIoT threats. Intrusion Detection Systems (IDS) have emerged as a critical layer of defense, broadly categorized into three methodologies:

- Signature-based IDS: Exceptional at identifying known exploit patterns but inherently blind to zero-day vulnerabilities.

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- Anomaly-based IDS: Employs machine learning to detect deviations from a defined "normal" baseline; however, these systems are frequently plagued by high false-positive rates in dynamic network environments.
- Hybrid IDS: Aims to synthesize the strengths of both approaches but often suffers from computational overhead and the mathematical challenges associated with manual hyperparameter configuration.

Document Overview

This research thesis presents the architecture and empirical evaluation of an optimized hybrid CNN-LSTM framework designed for IIoT security. By integrating deep learning (DL) for multi-dimensional feature extraction with Bayesian Optimization (BO) for automated model tuning, this study provides a robust, scalable defense mechanism capable of maintaining high-fidelity detection in heterogeneous industrial networks.

II. PROBLEM FORMULATION AND OBJECTIVES

Problem Statement

The deployment of effective IDS in IIoT environments is currently restricted by three fundamental bottlenecks:

1. High False-Detection Rates: Contemporary models often fail to distinguish between benign operational noise and malicious traffic, leading to "alert fatigue" among security analysts.
2. Computational Inefficiency: Many deep learning models are over-parameterized, making them unsuitable for real-time monitoring within the resource-constrained edge environments typical of IIoT.
3. Optimization Overhead: Conventional hyperparameter tuning methods—specifically manual grid search or heuristic-based algorithms like Particle Swarm Optimization (PSO) and Genetic Algorithms (GA)—are mathematically inefficient. These methods incur significant computational costs and often converge on local optima rather than the global maximum for model performance.

Research Objectives

This thesis establishes the following technical objectives to address the aforementioned gaps:

1. Architectural Hybridization: Design a "1+1" hybrid architecture consisting of a single Convolutional Neural Network (CNN) layer for spatial feature extraction and a single Long Short-Term Memory (LSTM) layer for temporal sequence modeling.
2. Automated Hyperparameter Optimization: Integrate a Bayesian Optimization framework to replace inefficient heuristic methods, utilizing the Tree-structured Parzen Estimator (TPE) for surrogate modeling.
3. Cross-Dataset Validation: Rigorously evaluate the framework across heterogeneous datasets—ToN-IoT and CICIoT2023—to ensure generalization stability.

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4. Metric Optimization: Achieve a verifiable reduction in false alarms while maximizing detection rates and ensuring the model remains computationally feasible for edge deployment.

III. LITERATURE SURVEY

Traditional vs. AI-Based IDS

The transition from legacy Host-based (HIDS) and Network-based (NIDS) systems to Artificial Intelligence (AI) has been driven by the need for predictive rather than reactive security. Albulayhi et al. (2021) established that while traditional signature-based methods remain a baseline, they are ineffective against the rapid evolution of IoT-specific malware. Conversely, Vinayakumar et al. (2019) demonstrated that deep neural networks (DNN) possess the intrinsic capability to identify emerging attack signatures across diverse platforms, outperforming classic host-specific monitors.

Current State of Hybrid Models

The following table delineates the architectural landscape of hybrid models in recent IIoT research:

Model Architecture	Key Features	Researcher(s)	Primary Benefit
Variational LSTM	Sequential dependency focus	Zhou et al. (2021)	Enhanced anomaly detection for industrial big data
CNN-LSTM	Spatial & Temporal hybrid	Gueriani et al. (2024)	High accuracy in capturing complex traffic patterns
CNN-LSTM-Autoencoder	Unsupervised DL integration	Ain et al. (2025)	Superior mitigation of large-scale DDoS attacks
LSTM-XGBoost	DL & Gradient Boosting	Sajid et al. (2024)	Improved collaborative detection in edge nodes

Gap Analysis

Despite these advancements, the reliance on manual tuning or heuristic methods (PSO, GA) remains a critical weakness. These approaches lack the adaptive efficiency required for modern cyber-defense. Bayesian Optimization addresses this by treating the tuning process as a sequence of informed decisions, utilizing past evaluation results to sample the most promising regions of the parameter space, thereby significantly reducing the computational budget required to achieve peak model performance.

IV. PROPOSED METHODOLOGY

Methodological Workflow

The system utilizes a linear progression from data ingestion to classification, as visualized in the framework [SOURCE_IMAGE_1]:

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1. Data Selection: Acquisition of high-fidelity IIoT traffic logs.
2. Preprocessing Pipeline: Formatting raw packets into model-ready tensors.
3. Model Instantiation: Construction of the hybrid CNN-LSTM layers.
4. Bayesian Tuning: Automated hyperparameter refinement.
5. Inference/Detection: Final classification of traffic as "Normal" or "Attack."

Data Preprocessing Pipeline

The pipeline ensures data quality through five distinct phases:

1. Data Cleaning: Systematic elimination of null entries and redundant records.
2. Feature Selection: Removal of non-contributory features (e.g., the 'difficulty' metric in NSL-KDD based variants) to minimize feature space dimensionality.
3. Min-Max Normalization: Rescaling all numerical input features to a standardized range of [0, 1] to ensure uniform gradient descent, utilizing the formal notation: \text{X}_{normalized} = \frac{X - X_{min}}{X_{max} - X_{min}}
4. One-Hot Encoding: Transformation of categorical protocol flags and service types into a machine-readable binary format.
5. Temporal Splitting: Segmenting the dataset into an 80% training partition and a 20% validation/testing partition.

Hybrid Model Architecture

As a Lead AI Architect, the priority was to design a "1+1" configuration to maximize stochastic efficiency:

- CNN Layer: A single convolutional layer extracts spatial features from the normalized input. It employs the ReLU activation function to facilitate non-linear learning and a Max-Pooling layer to down-sample feature maps while retaining high-impact spatial data.
- LSTM Layer: A single LSTM layer processes the output of the CNN to identify temporal dependencies. This layer maintains internal memory states to track sequence patterns over time. To prevent overfitting, dropout regularization is integrated into this layer.
- Output Layer: A fully connected dense layer maps the learned features to a final output. A sigmoid activation function provides the binary probability for classification.

Bayesian Optimization Framework

Hyperparameter tuning is executed via the Optuna library using the Tree-structured Parzen Estimator (TPE). TPE improves upon traditional methods by partitioning previous observations into two groups: "good" outcomes (above a performance threshold) and "bad" outcomes. It then samples the hyperparameter space by maximizing the probability of falling into the "good" group relative to the "bad." The optimization search space is defined as follows:

- CNN Filters: 32–128
- Kernel Size: 2–5
- LSTM Units: 32–128

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- Dense Units: 32–128
- Dropout Rate: 0.1–0.5
- Learning Rate: 10^{-4} to 10^{-2} (log-scaled)
- Batch Size: {64, 128, 256}

V. IMPLEMENTATION

Experimental Environment

- Software: Python environment utilizing TensorFlow/Keras for model architecture and Optuna for optimization logic.
- Hardware context: The experiments were conducted on a standard laptop to simulate the compute constraints of IIoT edge environments, proving the model's viability for on-device deployment without requiring data-center-grade GPUs.

Dataset Profiles

1. ToN-IoT: Sourced from UNSW Canberra, this dataset provides a modern representation of IIoT telemetry, including actual malicious activities like reconnaissance and data exfiltration.
2. CICIoT2023: Published by the Canadian Institute for Cybersecurity, this dataset offers a highly heterogeneous environment involving diverse devices (smart TVs, webcams) to test the model's resilience against botnets and advanced persistent threats.

Baseline vs. Optimized Variants

The research compared a Baseline CNN-LSTM (standard fixed parameters) against the Proposed BO-CNN-LSTM (optimized via Bayesian logic) to quantify the specific performance lift provided by the TPE framework.

VI. RESULTS

ToN-IoT Dataset Evaluation

The optimized model demonstrated a superior ability to identify malicious patterns within the ToN-IoT telemetry. Performance gains in accuracy and discriminative power are further verified by the ROC and bar charts in [SOURCE_IMAGE_2] and [SOURCE_IMAGE_3].

Table 1: Performance Comparison on ToN-IoT Dataset | Model | Accuracy | Precision | Recall | F1-score | ROC-AUC | | :--- | :--- | :--- | :--- | :--- | :--- | | CNN-LSTM (Baseline) | 97.98% | 98.54% | 97.40% | 97.97% | 0.9952 | | Proposed BO-CNN-LSTM | 99.19% | 99.21% | 99.17% | 99.19% | 0.9993 |

The confusion matrix for the ToN-IoT evaluation [SOURCE_IMAGE_4] confirms a significant reduction in both false positives and false negatives compared to the baseline.

CICIoT2023 Dataset Evaluation

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On the CICIoT2023 dataset, the model achieved near-optimal results, as evidenced by the performance metrics in [SOURCE_IMAGE_5] and the ROC curves in [SOURCE_IMAGE_6].
Table 2: Performance Comparison on CICIoT2023 Dataset | Model | Accuracy | Precision | Recall | F1-score | ROC-AUC | | :--- | :--- | :--- | :--- | :--- | :--- | | CNN-LSTM (Baseline) | 99.26% | 98.73% | 99.81% | 99.27% | 0.9972 | | Proposed BO-CNN-LSTM | 99.57% | 99.20% | 99.95% | 99.57% | 0.9991 |
The reduction in false positives on this dataset is visually detailed in the confusion matrix [SOURCE_IMAGE_7].

Key Finding Summary

- Peak Accuracy: 99.57% (CICIoT2023), representing a state-of-the-art result for hybrid architectures.
- Detection Fidelity: A recall of 99.95% ensures that almost no malicious traffic bypasses the detector.
- Optimization Lift: The ROC-AUC values above 0.999 across both datasets indicate near-perfect separability, validating the Bayesian approach.

VII. DISCUSSIONS

Comparative Analysis

To validate the model's competitive standing, a comprehensive comparative analysis against external benchmarks was conducted. The BO-CNN-LSTM demonstrates superior generalization stability across heterogeneous feature spaces.
Table 3: Comparative Performance Master Table (Binary Classification) | Author(s) & Year | Model Type | Dataset | Accuracy | F1-Score | | :--- | :--- | :--- | :--- | :--- | | Proposed Model (2025) | BO-CNN-LSTM | CICIoT2023 | 99.57% | 99.57% | | Proposed Model (2025) | BO-CNN-LSTM | ToN-IoT | 99.19% | 99.19% | | Yao et al. (2023) | LSTM-XGBoost | CICIoT2023 | 97.70% | 97.40% | | Gueriani et al. (2024) | CNN-LSTM | CICIoT2023 | 98.43% | 98.57% | | Abbas et al. (2024) | RNN | CICIoT2023 | 96.52% | 96.73% | | Ain et al. (2025) | CNN-LSTM+AE | CICIoT2023 | 96.78% | 96.00% | | Elghalhoud (2022) | DNN | ToN-IoT | 98.95% | 99.57% | | Elghalhoud (2022) | GBM | ToN-IoT | 98.55% | 99.18% | | Kim et al. (2020) | CNN-LSTM | CICIDS2017 | 91.93% | 86.47% |

The Impact of Bayesian Optimization

The transition from heuristic or manual tuning to Bayesian Optimization provided the "stochastic efficiency" required for high-performance IDS. By partitioning outcomes into "good" and "bad" distributions, the TPE algorithm effectively navigated the complex hyperparameter surface, avoiding the computational trap of PSO and GA methods. This resulted in a model that not only detects attacks more accurately but does so with a significantly smaller parameter footprint, making it ideal for edge implementation.

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VIII. CONCLUSION AND FUTURE SCOPE

Summary of Contributions

This research successfully established a hybrid CNN-LSTM IDS architecture that leverages Bayesian Optimization to solve the persistent challenges of high false-detection rates and optimization overhead. By using a single CNN and single LSTM layer, the model achieved state-of-the-art accuracy (99.57%) while maintaining the low computational complexity required for resource-constrained IIoT environments.

Future Directions

1. Multi-class Granularity: Transition from binary "Normal vs. Attack" detection to granular classification of specific attack types (e.g., Brute Force vs. Botnet).
2. Advanced Attention Mechanisms: Integration of Transformer-based attention to better capture long-range temporal dependencies in high-speed traffic.
3. Federated Learning Integration: Implementing decentralized training protocols to allow multiple industrial sites to collaborate on security models without sharing sensitive telemetry data.
4. Hardware Testbed Validation: Moving from simulated edge environments to real-world industrial hardware (PLCs and IoT Gateways) for field validation.

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Financial Challenges and Survival Strategies of Regional Football Clubs Empirical Evidence from Northern Uganda

Henry Omara
PhD Student, Department of Environmental Management, Selinus University of Science and Literature, Rome, Italy
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Abstract*—Regional football clubs in the developing world occupy a peculiar space in the sporting economy: socially indispensable, providing platforms for youth engagement, community identity and post-conflict healing, yet financially precarious in ways that threaten their existence. This study examines the financial challenges and survival strategies facing regional football clubs in Northern Uganda, using a mixed-methods approach that carefully analysed 200 questionnaire responses and 22 Key Informant Interviews (KIIs) with players, coaches, club officials and other football stakeholders across the region. Clubs generally operate within a survival-oriented financial system, leaning heavily on community contributions, owners' support and fundraising, while sponsorship and other commercial revenue remain limited. Key informants identified inadequate government support, unmet player welfare needs, transportation costs and low sponsorship as the major financial problems. These difficulties are not confined to one area of club activity; they spread across player motivation, match attendance, facility development, competition participation and overall club performance. In response, clubs have relied on volunteer support, community contributions and financial assistance from owners or management, while some have begun exploring local income sources such as poultry keeping, farming and small businesses, modest supplements rather than solutions on their own. The findings clearly show the core problem is not simply a lack of money but the absence of regular, diversified income capable of sustaining club activities over time; dependence on sponsorship, government support or occasional contributions leaves clubs financially weak and uncertain. Clubs therefore need genuinely diversified income-generating activities, stronger ties to government and private business, improved facilities and projects suited to the local environment. The study concludes that the central challenge is not simply the absence of money but the absence of predictable, diversified and institutionally supported revenue, a structural fragility demanding deliberate, multi-level intervention, and study proposes evidence-based recommendations for clubs, governing bodies, government and development partners.

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***Index Terms*—Regional football clubs; Financial challenges; Financial sustainability; Survival strategies; Northern Uganda; Revenue diversification**

I. INTRODUCTION

Football in Africa is evolving into a financially important and socially embedded sport across the continent, supported by an increasing number of clubs and an increasing awareness of the game's economic potential (Machela, 2025). At the continental level, the Confederation of African Football (CAF) has committed over USD 48 million per season to African club football, a figure that, while historically significant, remains almost entirely concentrated in elite continental competitions and carries almost no redistributive benefit to the regional clubs that constitute the vast majority of the African football ecosystem (CAF, 2026; Mabunda, 2025). Below the elite level, in the regional and community leagues where most African footballers play and where football's social functions, namely youth development, community cohesion, and cultural identity, are most immediately expressed, the financial reality is one of chronic scarcity, institutional neglect, and structural vulnerability (Oner et al., 2024).

In Uganda, this dynamic takes a particularly sharp form. Ugandan football is, as one commentator has accurately observed, more passion than business: an observation that captures both the genuine popular commitment to the sport and the persistent failure to convert that commitment into sustainable commercial and institutional structures (Drabe, 2025). National resource concentration at the elite level has left regional and lower-tier clubs structurally dependent on uncertain gate receipts, inconsistent community donations, and the personal financial commitment of club owners. This is a pattern that the federation's own governance reforms have done little to correct and that Uganda's National Sports Act (2023) and National Sports Regulations (2025) have heightened the registration, governance, financial accountability and compliance requirements for sports organisations and have increased the burden on under-resourced regional club (Kizza, 2025; Kuteesa, 2025; Krieger et al., 2020).

The global literature on football finance has developed substantially in the post-COVID period, with systematic reviews of European football financial regulation (Martin-Magdalena et al., 2024), assessments of the financial sustainability of English football leagues (Maguire and Philippou, 2023; Philippou and Maguire, 2022), and bibliometric analyses of financial management in sports clubs (Tabuk, 2024) providing increasingly sophisticated frameworks for understanding the mechanisms of football's financial health. Yet the vast majority of this literature addresses elite professional leagues, primarily in Europe and, to a lesser extent, urban South Africa, South America, and Australia. The financial mechanics of survival in lower-tier African regional football clubs, characterised by informal revenue structures, community-based solidarity mechanisms, and what might be described as survivalist management, remain almost entirely unaddressed in the peer-reviewed literature (Boya, 2016; Giampiccoli and Nauright, 2019).

Northern Uganda provides both an empirically urgent and theoretically distinctive context for addressing this gap. The Acholi and Lango sub-regions, encompassing districts including Gulu,

Lira, Kitgum, Pader, Kole, and Agago, continue to recover from the socio-economic devastation of the LRA conflict (1986 to 2008), which displaced approximately 1.8 million people, dismantled livelihoods and infrastructure, and profoundly disrupted the social fabric of communities across the north (Marshak et al., 2019). In this post-conflict landscape, grassroots football has emerged as a critical platform for youth engagement, psychological healing, and community reconciliation. These are functions that assign it social significance far beyond what its financial resources might suggest (Marshak et al., 2019; Giampiccoli and Nauright, 2019). The clubs that sustain this football ecosystem do so through improvisation, volunteerism, and community solidarity that formal financial management frameworks are not designed to capture or support.

This study is theoretically anchored in Resource Dependence Theory (RDT), which explains organisational behaviour and vulnerability through the dependence of organisations on external actors who control critical resources (Pfeffer and Salancik, 2003; Malatesta and Smith, 2014). For regional football clubs in Northern Uganda, RDT's core propositions map directly onto their operational reality. They are highly dependent on a narrow and uncertain resource base dominated by community goodwill and individual patronage. This dependence produces vulnerability because resources are controlled by actors whose priorities and capacities are themselves volatile. Sustainability therefore requires either reducing dependence through internal resource development or managing dependence through strategic relationships that provide more predictable external support (Jiang et al., 2023; Mrkonjic, 2023; Choi et al., 2023). The COVID-19 pandemic revealed the full cost of this structural fragility for grassroots sport globally, when the disruption of community-based funding mechanisms exposed the absence of alternative revenue infrastructure and forced many clubs toward institutional collapse (ICSS, 2021).

The intersection of digital innovation and community-based sport financing offers one important avenue for the development of more resilient revenue structures. Atlantic Council analysis (Bonsundy-O'Bryan, 2026) documents the growing relevance of digital platforms, merchandise, and social media fundraising for African football clubs, while Alonso et al. (2024) demonstrates how social entrepreneurship frameworks can support community development through sport even in resource-constrained environments. At the same time, Getnet et al. (2025) demonstrate that revenue diversification and broadcasting income remain structurally underdeveloped even in more established African leagues like the Ethiopian Premier League. The emerging Ugandan sports governance framework, including the National Sports Act (2023), creates regulatory structures that could either support or further constrain regional clubs depending on how they are implemented and resourced (Kizza, 2025; Garmamo et al., 2024).

The resource-based perspective on sport organisation sustainability, developed and applied by Choi et al. (2023) in the context of sport-for-development organisations, argues that sustainability depends not only on available financial resources but on the organisational assets, capabilities, and governance structures that determine whether resources can generate value over time. This perspective explains why identical resource constraints can produce different sustainability outcomes in different clubs: governance quality, management capacity, community embeddedness, and the ability to develop and manage strategic relationships all mediate the

relationship between resource scarcity and organisational survival (Mrkonjic, 2023; Garmamo et al., 2024).

Against this theoretical background, this study employs a convergent mixed-methods design, integrating 200 questionnaire responses with 22 Key Informant Interviews, to produce a comprehensive and empirically grounded account of the financial challenges and survival strategies of regional football clubs in Northern Uganda. The study makes four principal contributions. First, it provides the first systematic empirical analysis of the financial mechanics of regional football club survival in a post-conflict African context. Second, it documents the prevalence, severity, and operational consequences of specific financial challenges across a representative multi-district sample. Third, it identifies and characterises the locally adapted survival strategies that clubs have developed in the absence of formal financial support. Fourth, it proposes actionable recommendations grounded in the study's empirical findings and theoretically informed by the RDT framework.

Problem Statement

Regional football clubs in Northern Uganda operate under conditions of acute financial precarity, with little institutional support from state authorities or national football governing bodies. Despite the critical social role that these clubs play in post-conflict youth engagement and community rebuilding, they are forced to rely on ad hoc community donations and the personal financial commitment of individual club owners. This dependence produces multiple operational failures: inability to pay player allowances, accumulating transport debts, repeated fixture postponements, and difficulty retaining talented players. Without a systematic understanding of the financial dynamics driving these challenges and the survival strategies that clubs have developed in response, the broader project of building a sustainable football ecosystem in Northern Uganda, one capable of supporting talent development, community resilience, and social integration, will remain structurally compromised.

Research Gap

The academic literature on football finance is heavily concentrated on European elite leagues and, to a lesser extent, urban professional clubs in South Africa, Ethiopia, and other established African football markets. While some scholarship addresses African sport development, it has generally focused on social outcomes such as cohesion, identity, and post-conflict healing, rather than the financial mechanics of organisational survival in resource-constrained environments. The specific financial challenges, informal survival strategies, and locally adapted income-generation approaches of grassroots clubs in post-conflict, rural African contexts represent a substantial and consequential empirical gap that this study addresses.

Research Objectives

- To identify the primary sources of funding and revenue available to regional football clubs in Northern Uganda.
- To examine the most critical financial challenges facing these clubs and their cascading effects on operational stability and sporting performance.

- To assess the effectiveness of survival strategies currently adopted by clubs to mitigate financial scarcity, distinguishing between short-term coping mechanisms and longer-term sustainability approaches.
- To recommend actionable measures for improving the financial sustainability and professionalisation of regional football clubs and leagues in Northern Uganda.

Research Questions

- What are the major sources of funding for regional football clubs in Northern Uganda, and how adequate and predictable are these sources?
- What are the most serious financial challenges hindering club operations and performance, and through what mechanisms do they affect sporting and administrative functions?
- How do regional clubs utilise community-based assets, volunteer networks, and informal income-generating activities to remain operational, and how effective are these mechanisms?
- What structural, institutional, and managerial measures would most effectively support the transition from financial survival to financial sustainability in Northern Uganda's regional football clubs?

II. RESEARCH METHODOLOGY

Research Design

This study employed a convergent parallel mixed-methods design (Creswell and Creswell, 2020), integrating quantitative survey data with qualitative Key Informant Interview evidence to produce a comprehensive understanding of regional football clubs' financial dynamics. The convergent design allows quantitative and qualitative strands to be developed independently and then merged at the interpretation stage, enabling the researcher to assess where findings confirm, extend, or contradict one another, thereby producing a more robust and nuanced account than either method alone could generate (Kawar et al., 2024). The quantitative strand establishes the prevalence and severity of financial challenges across the study population, while the qualitative strand explains the mechanisms, meanings, and institutional dynamics behind those patterns. The mixed-methods approach is particularly well suited to this research context because the financial challenges of regional football clubs operate simultaneously at the statistical level, where quantitative data on revenue sources, challenge ratings, and survival strategies are needed, and at the experiential and institutional level, where they lived perspectives of club managers, coaches, and administrators reveal dimensions that survey data cannot capture. The post-conflict and resource-constrained setting further supports methodological plurality, as locally adapted survival mechanisms and informal management practices require the interpretive depth of qualitative inquiry to be adequately documented (ICSS, 2021).

Study Area

The study was conducted across 10 districts in the Acholi and Lango sub-regions of Northern Uganda: Lira, Gulu, Kole, Pader, Alebtong, Kwania, Agago, Otuke, Amolatar and Amuru. These

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districts were selected to represent the geographic diversity of the Northern Uganda football landscape while concentrating on sub-regions where the LRA conflict's impact on social institutions, including grassroots football, was most severe and where the post-conflict recovery process provides the most instructive context for studying sport sustainability under resource constraints. Lira and Gulu, as the largest urban centres of the Lango and Acholi sub-regions respectively, provide the institutional anchor for regional football administration, while the smaller districts contribute the rural and peri-urban contexts where financial challenges are most acute (Marshak et al., 2019).

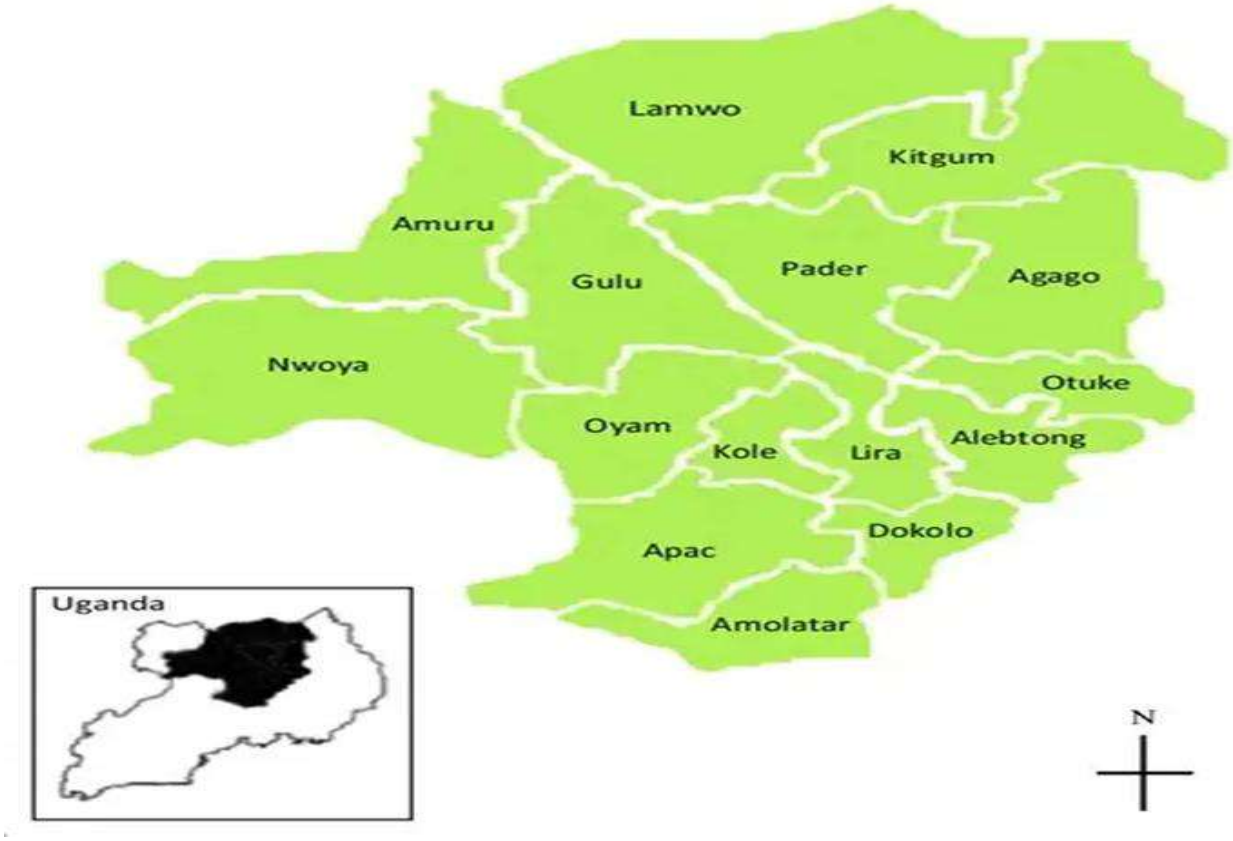


Figure 1. Map Showing the Regional Football Club Study Districts in Northern Uganda.

Sampling

The study participants comprised of all active stakeholders in regional football clubs across the 10 study districts, including players, coaches, club administrators, volunteers, and other associated stakeholders. A purposive sampling approach was used to select participants with direct experience of the financial realities and management practices of regional clubs. For the questionnaire component, a systematic approach was used to identify 200 participants across the 10 districts, in approximate proportion to the size and football activity of each district. The questionnaire link was shared across various football clubs' WhatsApp platforms, along with guidance on how to complete it. While for the Key Informant Interview (KII) component, purposive criterion sampling, supported by the regional league administrator, was used to identify 22 participants with

authoritative knowledge of football administration. These included club CEOs, managers, chairpersons, head coaches, technical directors, team doctors, league administrators, and match officials from the Northern Regional Football Association.

Data Collection Methods

Structured Questionnaire: Structured questionnaires were administered to 200 participants across the 10 study districts. The questionnaire was designed in four thematic sections: first, participant profile covering role, district, and years of football experience; second, revenue and financial structure covering identification of major, minor, and non-revenue sources across ten categories; third, financial challenge severity covering rating of twelve specific financial challenges on a five-point Likert scale from 1 (Not Serious) to 5 (Very Serious), with a supplementary item identifying the single biggest financial challenge; and fourth, survival strategies and sustainability covering rating of the most effective survival strategies, patterns of income-generating activity adoption, and identification of priority measures for financial sustainability. The questionnaire was pilot-tested with five club officials in Lira and Kole before deployment to ensure clarity and face validity.

Key Informant Interviews: 22 semi-structured Key Informant Interviews were conducted with authoritative stakeholders selected to provide institutional and operational perspectives on the financial management of regional football clubs. KII participants included club CEOs (n = 3), managers (n = 4), chairpersons (n = 4), head coaches (n = 4), technical directors (n = 2), a team doctor, a match official, a competition statistician, a government sports official, and a league administrator from the Northern Regional Football Association. Interviews ranged from 20 to 30 minutes and were conducted online using Kobo Collect link shared in different football WhatsApp forums with clear instructions on how to complete the study. A semi-flexible guide was used, covering five thematic domains: funding sources and adequacy; financial challenge severity and operational effects; survival strategies and their effectiveness; barriers to commercial development; and stakeholder recommendations for financial sustainability. All interviews were complete with consent by all the participating individuals.

Data Analysis

Quantitative data from the 200 questionnaires were processed using Microsoft Excel. Descriptive statistics, including frequency counts, percentages, and means, were computed for all Likert-scale and categorical items. Mean seriousness scores for financial challenges were calculated by assigning numerical values (1 to 5) to Likert responses and computing the weighted arithmetic mean across the 200 valid responses per item. Results are presented in ranked order by mean score to enable direct comparison of challenge severity. The two-part sponsorship analysis, presenting both the seriousness rating and the biggest challenge item, was designed to capture the full dimensionality of the sponsorship problem rather than reducing it to a single metric. Qualitative data from the 22 KII transcripts were analysed using a data-driven reflexive thematic analysis

approach following Braun and Clarke's (2024) updated guidance. This involved transcribing audio recordings, conducting first-cycle descriptive coding to identify recurring themes across the dataset, and second-cycle pattern coding to develop sub-categories, particularly around survival typologies, institutional relationships, and locally adapted income-generation mechanisms. The coding process was iterative, with themes reviewed against the full dataset to ensure their grounding in the evidence. At the integration stage, a convergence matrix was constructed to systematically compare questionnaire findings and KII themes for each analytical domain, identifying areas of confirmation, extension, and apparent divergence between the two data sources.

Ethical Considerations

The study adhered to rigorous ethical standards appropriate for community-based research in a post-conflict setting. Informed consent was obtained from all participants, including questionnaire respondents and key informant interview (KII) participants, prior to their participation in the study. The purpose of the study, the voluntary nature of participation, and the consent statement were clearly explained in the introductory sections of the questionnaires and KII guides. Participants were explicitly informed of their right to decline participation or withdraw from the study at any stage without consequence. Confidentiality and anonymity were maintained throughout the research process. KII participants were identified only by their professional role and district, and no personally identifying information was included in research records or publications. All completed questionnaires and research data were stored on an encrypted, password-protected server accessible only to the researcher and will be securely deleted upon completion of the study in accordance with applicable data protection requirements. Given the history of conflict and its implications for social trust in Northern Uganda, particular care was taken to ensure that participation was not perceived as surveillance, mandatory reporting, or an activity associated with government authorities, security agencies, or football association functions. Participants were reassured that the information they provided would be used solely for academic research and would not affect their access to services, relationships with authorities, or participation in football-related activities (Ataullahjan et al., 2022). Finally, all secondary sources used in the study were appropriately acknowledged, accurately represented, and referenced in accordance with accepted academic and research integrity standards.

Limitations of the Study

Four limitations shape the scope and confidence of this study's findings. First, the study's coverage of nine districts in the Acholi and Lango sub-regions, while providing a representative Northern Uganda sample, does not extend to West Nile or other northern sub-regions, meaning that findings cannot be extrapolated to all of Northern Uganda's diverse football contexts. Second, the mixed-methods design produces rich and internally consistent evidence, but the cross-sectional nature of the data collection means that the study documents financial conditions at a specific moment rather than tracking how financial challenges or survival strategies evolve over time. Longitudinal

follow-up research would be needed to assess the durability of the emerging income-generating activities identified in the KII evidence. Third, survey responses on financial challenge severity are subjective assessments rather than objective financial measurements. The absence of club-level financial records, which most clubs do not maintain in accessible or complete form, means that the study documents perceptions of financial challenges rather than their quantitative magnitude. Fourth, social desirability effects may have led some KII participants to emphasise positive survival strategies and understate the degree of financial fragility, particularly where clubs have governance relationships with regional football associations whose support they value. The consistency of evidence across multiple independent KII participants and the convergence between questionnaire and KII findings provide some mitigation for this risk.

III. RESULTS AND FINDINGS

Profile of Study Participants

Table 1 presents the geographic, experiential, and role profile of the 200 questionnaire respondents. Players constituted the largest group (97; 48.5%), followed by club officials (60; 30.0%), providing perspectives from both the sporting and administrative dimensions of regional football. The majority of respondents had substantial football experience: 86 (43.0%) had six to ten years of involvement, and a further 70 (35.0%) had more than ten years. Only 2 respondents (1.0%) had less than two years of experience, confirming that the sample provided grounded, experience-based perspectives.

Table 1: Geographic and Demographic Profile of Questionnaire Respondents (N = 200).

District	Lira	Gulu	Kole	Pader	Alebtong	Kwania	Agago	Otuke	Amuru	Total
Number (N)	71	41	27	18	11	10	9	8	5	200
Percent (%)	35.5	20.5	13.5	9.0	5.5	5.0	4.5	4.0	2.5	100.0

Football Experience	Under 2 years	2 to 5 years	6 to 10 years	Over 10 years	Total
Number N)	2	42	86	70	200
Percent (%)	1.0	21.0	43.0	35.0	100.0

Role / Position	Player	Club Official	Coach	Other	Volunteer	Total
Number (N)	97	60	19	21	3	200
Percent (%)	48.5	30.0	9.5	10.5	1.5	100.0

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Source: Questionnaire Survey (2026).

The 22 KII participants brought substantial institutional experience. Thirteen of the 22 informants had at least six years of direct involvement in football administration, with individual experience levels ranging from 6 to 20 years. This depth of institutional knowledge strengthened the qualitative evidence considerably, ensuring that KII accounts reflected sustained exposure to the financial realities of regional football rather than short-term or limited operational perspective.

Financial Structure and Revenue Sources

Table 2 presents the revenue structure of regional football clubs as reported by the 200 questionnaire respondents. The data reveal a funding ecosystem characterised by extreme reliance on informal, community-based, and owner-dependent sources, with commercial, institutional, and diversified revenues playing marginal or negligible roles.

Table 2: Major, Minor, and Non-Revenue Sources of Regional Football Clubs (N = 200).

Revenue Source	Major Source – N (%)	Minor Source – N (%)	Not a Source - N (%)
Community contributions	79 (39.5)	86 (43.0)	35 (17.5)
Fundraising events	40 (20.0)	79 (39.5)	81 (40.5)
Gate collections	29 (14.5)	75 (37.5)	96 (48.0)
Donations	27 (13.5)	72 (36.0)	101 (50.5)
FUFA support	26 (13.0)	69 (34.5)	105 (52.5)
Sponsorship	23 (11.5)	67 (33.5)	110 (55.0)
Player transfers	23 (11.5)	55 (27.5)	122 (61.0)
Membership fees	19 (9.5)	72 (36.0)	109 (54.5)
Merchandise sales	18 (9.0)	56 (28.0)	126 (63.0)
Government support	12 (6.0)	18 (9.0)	170 (85.0)

Source: Questionnaire Survey (2026).

Community contributions were the most prominent major source, identified by 79 respondents (39.5%): a finding that reflects the centrality of community solidarity in sustaining clubs whose formal revenue mechanisms are weak or absent. Fundraising events were the second-ranked major source (40; 20.0%). By contrast, government support was identified as a major source by only 12 respondents (6.0%), and 170 (85.0%) classified it as not a source at all, the starkest single indicator of institutional neglect in the study's quantitative data. Sponsorship, despite being the most urgently desired revenue source as Section 7.4 demonstrates, was identified as a major source by

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only 23 respondents (11.5%), with 110 (55.0%) reporting it as not a source. The KII evidence strongly reinforces these patterns. Club-owner contributions were cited by 14 of the 22 informants, while community fundraising was identified by 10. Sponsorship from local businesses was cited by only six informants, and FUFA support by just one: a finding that challenges the assumption that national federation structures provide meaningful financial support to the clubs in their base pyramid.

"The funding is completely inadequate. Clubs depend entirely on what owners can give and what the community can contribute. When neither is available, they simply cannot function. There is no clear system for generating club revenue - just goodwill." KII-03, League Administrator, Lira

Financial Challenge Severity

Table 3 presents the twelve financial challenges ranked by their mean seriousness score across the 200 respondents. All twelve challenges recorded means above 3.0 out of 5.0, indicating that respondents assessed all identified challenges as at least moderately serious. The top four challenges all produced means above 4.10, indicating that inadequate government support, player welfare expenses, transportation costs, and lack of sponsorship are each perceived as serious to very serious across the majority of the study population.

Table 3: Ranking of Financial Challenges by Mean Seriousness Score (N = 200).

Financial Challenge	Mean /5.0	Most Frequent Response (N and %)	Rank
Inadequate government support	4.14	Very Serious: 142 (71.0%)	1
Player welfare expenses	4.13	Very Serious: 116 (58.0%)	2
Transportation costs	4.12	Very Serious: 119 (59.5%)	3
Lack of sponsorship	4.10	Very Serious: 123 (61.5%)	4
Medical expenses	3.96	Very Serious: 90 (45.0%)	5
Low gate collections	3.92	Very Serious: 112 (56.0%)	6
Low merchandise sales	3.91	Very Serious: 116 (58.0%)	7
Equipment costs	3.84	Very Serious: 87 (43.5%)	8
Poor infrastructure	3.81	Very Serious: 82 (41.0%)	9
Inadequate FUFA support	3.77	Very Serious: 95 (47.5%)	10
Limited media coverage	3.75	Very Serious: 99 (49.5%)	11
Refereeing costs	3.29	Moderately Serious: 67 (33.5%)	12

Source: Questionnaire Survey (2026).

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The distinction between seriousness rating and biggest single challenge produced analytically important results. Although inadequate government support recorded the highest mean seriousness (4.14 out of 5.0), lack of sponsorship was identified by 143 respondents (71.5%) as the biggest financial challenge facing their club. This suggests that while government failure is perceived as the most structurally damaging problem, sponsorship deficit is experienced as the most operationally urgent and practically addressable constraint. Table 4 presents this distribution.

Table 4: Biggest Single Financial Challenge Reported by Respondents (N = 200).

Biggest Financial Challenge	Lack of Sponsorship	Transportation Costs	Player Welfare Expenses	Low Attendance	Equipment Shortages	Total
Number (N)	143	33	13	7	4	200
Percent (%)	71.5	16.5	6.5	3.5	2.0	100.0

Source: Questionnaire Survey (2026).

Transportation as a Strategic Constraint

Transportation recorded a mean seriousness of 4.12 out of 5.0, with 119 respondents (59.5%) rating it Very Serious. What distinguishes transportation from other financial challenges is its direct operational consequence: 162 respondents (81.0%) agreed or strongly agreed that financial constraints affect away-match participation, a finding that makes transportation not merely an administrative cost but a determinant of competitive participation. Table 5 presents the KII evidence on transportation's specific operational effects.

Table 5: KII Evidence on Transportation and Its Operational Effects (N = 22).

KII Finding on Transportation	N out of 22 Informants
Transportation reduces away-match participation	15
Transportation increases club debt	12
Clubs forced to travel on match day due to lack of overnight funds	10
Costs limit participation in distant competitions	9
Transportation reduces training budgets	8
Transportation reduces player-welfare spending	8
Costs contribute to fixture postponements	5

Source: Key Informant Interviews (2026).

The convergence of questionnaire and KII evidence on transportation reveals it as a mechanism through which financial scarcity translates directly into competitive disadvantage. Clubs that cannot afford away travel must reduce competition participation, which reduces gate receipts, weakens competitive development, reduces player motivation, and diminishes the club's profile, making it less attractive to potential sponsors. Transportation cost is therefore not a single operational challenge but an entry point into a cycle of financial and sporting decline.

Player Welfare, Morale, and Retention

Table 6 documents the breadth of operational effects attributable to financial constraints across player welfare, training, and competitive domains. The consistency of high agreement rates across all seven indicators, ranging from 71.0% to 82.5%, establishes that financial pressure affects virtually every dimension of club operations.

Table 6: Operational Effects of Financial Constraints on Club Operations (N = 200).

Operational Effect	Agree (N)	Strongly Agree (N)	Total N (%)
Financial challenges affect player performance	52	113	165 (82.5)
Financial constraints affect away-match participation	23	139	162 (81.0)
Financial problems affect league competitiveness	24	136	160 (80.0)
Failure to pay allowances affects operations	63	91	154 (77.0)
Financial constraints reduce training quality or frequency	70	79	149 (74.5)
Difficulty retaining talented players	47	101	148 (74.0)
Financial constraints cause match postponements	56	86	142 (71.0)

Source: Questionnaire Survey (2026).

“The players are committed but they see how we struggle. When we cannot pay allowances and cannot afford keeping players at the training camp, the best ones begin to look elsewhere. We are developing talent for other clubs because we cannot keep them.” KII-16, Club Mobilizer, Kole

Infrastructure Constraints

Poor infrastructure received a mean seriousness rating of 3.81 out of 5.0, with 82 respondents (43.9% of valid responses) rating it Very Serious and a further 43 (23.0%) rating it Serious. Table 7 integrates questionnaire and KII evidence to document the multiple financial pathways through which infrastructure weakness affects club sustainability.

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Table 7: Integrated Questionnaire and KII Evidence on Infrastructure Constraints.

Infrastructure Issue	Questionnaire Evidence (N=200)	KII Evidence (N=22)	Interpretation
Poor infrastructure overall	Mean 3.81/5; 82 (43.9%) Very Serious	22 of 22 informants reported at least one infrastructure-finance problem	Substantial financial constraint, though not the highest-ranked
Poor pitches and injury risk	Not directly measured	15 of 22 informants reported that poor pitches increase injuries	Indirect cost through player welfare and medical expenses
Ground and stadium rental	Not directly measured	7 of 22 informants reported heavy spending on rented facilities	Recurring participation costs from absence of owned facilities
Effect on attendance and revenue	127 of 200 (63.5%) reported that financial constraints affect fan attendance	8 of 22 reported reduced attendance; 9 of 22 reported reduced commercial activity	Infrastructure weakness reduces match-day income
Effect on sponsorship attraction	Sponsorship was the biggest challenge for 143 of 200 (71.5%)	6 of 22 informants specifically identified poor infrastructure as discouraging sponsors	Infrastructure links to the wider commercialisation problem
Infrastructure investment recommended	75 of 200 (37.5%) recommended improvement	6 of 22 informants called for infrastructure development	Stakeholders view infrastructure improvement as part of the long-term solution

Source: Questionnaire Survey and Key Informant Interviews (2026).

The most analytically important insight from Table 7 is that infrastructure operates through multiple connected financial pathways rather than as a single cost item. Clubs pay to access facilities they do not own; poor pitches generate additional injury and medical costs; inadequate venues reduce spectator attendance and commercial activity; and poor infrastructure weakens the club's profile for potential sponsors. Infrastructure is therefore a strategic financial issue rather than simply an operational facility problem.

Institutional and Governing-Body Support

The data on institutional support reveal a fundamental disconnect between the regulatory presence of governing bodies and their financial contribution to club sustainability. Inadequate government

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support recorded the highest seriousness mean (4.14 out of 5.0), with 142 respondents (71.0%) classifying it Very Serious. Yet only 12 respondents (6.0%) identified government support as an actual funding source and 170 (85.0%) reported it as not a source. Tables 8 and 9 present the quantitative and qualitative evidence on this institutional gap.

Table 8: Questionnaire Evidence on Institutional Support Challenges (N = 200).

Institutional Challenge	Very Serious n (%)	Mean /5.0
Inadequate government support	142 (71.0)	4.14
Inadequate FUFA support	95 (47.5)	3.77
Limited media coverage	99 (49.5)	3.75

Source: Questionnaire Survey (2026).

Table 9: Types of Governing-Body Support Reported by KII Informants (N = 22).

Type of Support Provided by Governing Bodies	KII (N) out of 22
Technical guidance	13
Club licensing and registration support	10
Competition organisation	8
Capacity-building workshops	8
Referee services	7
Youth football programmes	6
Equipment donations	3
Direct financial support	1

Source: Key Informant Interviews (2026).

The KII evidence makes the institutional resource mismatch explicit. Governing-body support is concentrated in technical, regulatory, and organisational functions, including competition management, licensing, and workshops, while direct financial or material support is almost entirely absent. Only one of 22 informants reported receiving direct financial support from a governing body. This creates a situation in which clubs bear increasing regulatory compliance burdens without receiving the financial resources that compliance requires: a dynamic that several KII informants characterised as more regulations than resources.

The Sponsorship and Commercialisation Gap

The sponsorship findings represent one of the study's most analytically consequential patterns. Sponsorship was simultaneously the biggest financial challenge (identified by 143; 71.5% of

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respondents) and one of the least frequently occurring funding sources (major source for only 23; 11.5%). This gap between sponsorship needs and sponsorship reality reflects not merely the absence of willing sponsors but the absence of the organisational capabilities that would make clubs attractive to potential sponsors. Table 10 identifies the specific barriers reported by KII informants.

Table 10: KII-Identified Barriers to Sponsorship Attraction (N = 22).

Barrier to Sponsorship Attraction	KII (N) out of 22
Low media exposure	15
Poor marketing skills	12
Weak club branding	11
Poor financial accountability and reporting	9
Absence of formal sponsorship proposals	9
Limited digital presence	9
Small fan base	9
Economic hardship of potential local sponsors	8
Competition from larger and higher-profile clubs	4

Source: Key Informant Interviews (2026).

The barrier profile reveals that clubs face a commercialisation gap: they need sponsorship more urgently than almost any other financial intervention, but they lack the media visibility, marketing capacity, professional branding, financial transparency, and commercial propositions that would make them credible investment partners for corporate or business sponsors. Low media exposure (15 out of 22 informants) and poor marketing skills (12 out of 22) indicate that this is not primarily a supply problem where willing sponsors are absent, but a visibility and presentation problem where clubs cannot effectively communicate their value to potential partners.

Survival Strategies in Practice

Table 11 presents the most effective survival strategies reported by questionnaire respondents. Three strategies, namely volunteer services, club-owner support, and community fundraising, account for 179 responses (89.5%) of the total, establishing the near-complete dominance of informal, relationship-based survival mechanisms over formal commercial approaches.

Table 11: Most Effective Survival Strategies Reported by Respondents (N = 200).

Survival Strategy	Number	% of 200
Volunteer services	63	31.5

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Survival Strategy	Number	% of 200
Club-owner financial support	58	29.0
Community fundraising	58	29.0
Youth player development	8	4.0
Merchandise sales	8	4.0
Business partnerships	5	2.5
Total	200	100.0

Source: Questionnaire Survey (2026).

The KII evidence confirms this reliance while critically assessing its adequacy. Community fundraising was identified as an adopted strategy by 13 informants, membership contributions by 14, and volunteer labour by 12. However, informants were consistent in characterising these mechanisms as temporary and insufficient for long-term organisational development.

"We use what is available. Community support, our own money as management, and volunteers. It keeps us alive. But alive is not the same as developing. We need to reach a point where we can plan for next season, not just survive to next month." KII-01, Head Coach, Kole.

Emerging Alternative Income-Generating Activities

A particularly noteworthy finding from the KII data is the emergence of small-scale, locally adapted income-generating activities among a minority of clubs. Nine of the 22 informants (40.9%) reported that their clubs had developed at least one alternative income-generating activity. Table 12 presents the distribution of these activities.

Table 12: Alternative Income-Generating Activities Identified by KII Informants (N = 22).

Income-Generating Activity	KII (N) out of 22
Farming projects (crops and vegetables)	5
Merchandise sales	4
Academy fees	1
Event management	1
Facility rentals	1
Betting partnerships	1

Source: Key Informant Interviews (2026).

Farming projects, reported by five informants from different districts, represent the most geographically distributed and culturally embedded form of income diversification in the dataset.

The appearance of farming across multiple, independent KII accounts from distinct districts, including Amolatar, Lamwo, Nwoya, and Apac, suggests that agricultural income generation reflects a genuine, locally adapted strategy rather than an isolated or idiosyncratic practice. This finding is analytically significant because it demonstrates that diversification in this context does not follow the commercial model that dominates the football finance literature. Instead, it takes forms that are commensurate with local economic realities and available resources.

Financial Risk Management

The KII evidence on financial risk management reveals a significant imbalance. Clubs are substantially more likely to manage financial scarcity by controlling expenditure than by creating new revenue. Table 13 presents the distribution of risk management measures.

Table 13: Financial Risk Management Measures Reported by KII Informants (N = 22).

Financial Risk Management Measure	KII (N) out of 22
Budget controls	14
Financial audits	7
Cost reduction measures	7
Financial planning	7
Emergency reserves	5
Debt-control mechanisms	5
Sponsorship agreements	2
Revenue diversification	1

Source: Key Informant Interviews (2026).

The contrast between budget control (adopted by 14 of 22 informants) and revenue diversification (adopted by only 1 of 22) is the most analytically revealing finding in this section. It documents a financial management orientation that prioritises limiting outgoings over expanding income. This is rational in acute resource scarcity but insufficient as a basis for organisational sustainability. Cost reduction can protect short-term survival but cannot by itself generate the surplus needed for infrastructure investment, staff development, commercial visibility, or the improvement of the club's financial attractiveness to external partners.

Stakeholder Priorities for Financial Sustainability

Tables 14 and 15 present the convergent evidence on what stakeholders believe is needed to move clubs from financial survival to financial sustainability. The combined evidence points toward a multi-intervention model rather than any single solution.

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Table 14: Priority Measures for Financial Sustainability as Ranked by KII Informants (N = 22).

Priority Measure	KII (N) out of 22
Improve sponsorship attraction	15
Connect clubs to sponsors through institutional facilitation	14
Increase governing-body financial support	14
Increase fan engagement and attendance	11
Diversify revenue sources	11
Professionalise club administration	10
Develop youth academies	9
Improve financial management capacity	9
Enhance media coverage	8
Strengthen governance structures	7

Source: Key Informant Interviews (2026).

Table 15: Priority Forms of External Support Identified by Questionnaire Respondents (N = 200).

Priority Form of External Support Needed	Number	% of 200
Direct financial assistance	102	51.0
Sponsorship facilitation	61	30.5
Infrastructure development	37	18.5
Total	200	100.0

Source: Questionnaire Survey (2026).

The convergence is instructive. Stakeholders identify sponsorship improvement, revenue diversification, institutional support, professionalisation, governance, media visibility, and fan engagement as complementary priorities rather than sequential ones. This reflects the systemic character of the financial sustainability challenge: it cannot be resolved by addressing any single lever while leaving others unchanged. A club that receives direct financial assistance without improving governance or commercial presentation will not attract sustainable sponsorship. A club that improves its commercial presentation without infrastructure cannot retain sponsors or generate fan revenue.

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IV. DISCUSSION

The evidence assembled across 200 questionnaire responses and 22 Key Informant Interviews produces a picture of regional football club financial management in Northern Uganda that is internally consistent, analytically coherent, and practically urgent. Across instruments, geographic districts, and respondent types, the findings converge on the same central conclusion: regional football clubs in Northern Uganda are financially alive but not financially sustainable, and the mechanisms that keep them alive are systematically insufficient to create the conditions for long-term organisational development.

The Distinction Between Survival and Sustainability

The most important analytical contribution of this study is the empirical substantiation of the distinction between financial survival and financial sustainability in the context of African regional football. Survival mechanisms, including volunteerism, community fundraising, and owner support, are characterised by their relationship-dependence, their informality, and their orientation toward meeting immediate obligations rather than building organisational capacity. Sustainability mechanisms, including diversified and predictable revenue, formal governance, commercial relationships, and physical assets, are characterised by their institutional embeddedness, their capacity to compound over time, and their ability to generate surplus that can be reinvested. The study's data establish that Northern Ugandan regional clubs are overwhelmingly oriented toward survival, while acknowledging both the genuine resilience this survival represents and its structural inadequacy as a foundation for long-term institutional development (Oner et al., 2024; Choi et al., 2023).

This finding extends and empirically grounds Resource Dependence Theory in a context that the original formulation, developed primarily for large organisations in advanced economies, did not anticipate (Pfeffer and Salancik, 2003; Malatesta and Smith, 2014). In post-conflict Northern Uganda, the resource dependence of regional football clubs has distinctive features: the primary external resources on which clubs depend are not financial capital or market access but community social capital, namely goodwill, volunteerism, and collective identity, whose conversion into financial sustainability requires institutional bridges that currently do not exist.

The Commercialisation Gap and Its Structural Character

The sponsorship findings, where 71.5% identified lack of sponsorship as the biggest challenge but only 11.5% identified it as a major funding source, document a commercialisation gap whose structural character is clearly established by the KII evidence. This is not a gap that will close spontaneously as clubs continue to operate. It requires deliberate intervention to develop the visibility, marketing capacity, financial transparency, digital presence, and governance quality that convert commercial interest into actual partnership. The identification of low media exposure (15 out of 22 informants) and poor marketing skills (12 out of 22) as the two leading barriers to sponsorship confirms that the problem is as much about clubs' capacity to present themselves effectively as it is about the availability of willing sponsors. This finding is consistent with the broader argument that financial sustainability in football requires professional management

capabilities, not simply goodwill or community support (Martin-Magdalena et al., 2024; Machela, 2025).

Locally Adapted Diversification as an Emergent Pathway

The farming finding is the study's most theoretically innovative result. Agricultural income generation represents a form of locally adapted social entrepreneurship that does not map onto the commercial models, such as broadcasting, merchandise, and academy partnerships, that dominate the football finance literature, but is entirely appropriate to Northern Uganda's agro-ecological and economic context. It generates independent revenue that does not depend on community goodwill, commercial markets, or institutional support. It engages the club's physical assets and the labour of volunteers and players in ways that produce both financial returns and community solidarity. And it suggests a development trajectory that is organic rather than imposed, arising from clubs' own assessment of their available resources and realistic income-generation opportunities (Alonso et al., 2024; Giampiccoli and Nauright, 2019).

The Institutional Resource Mismatch

The finding that 85.0% of respondents identified government support as not a funding source, while 71.0% rated inadequate government support as Very Serious, documents an institutional abandonment that has been particularly consequential in a post-conflict recovery context where the state's social reconstruction function is most critical. The contrast between governing-body regulatory presence and financial absence creates a compliance burden without a support infrastructure, a pattern that Krieger et al. (2020) identify as a structural risk in sports governance reform across contexts where institutional capacity lags behind regulatory ambition. The implication is not that regulation should be reduced but that it should be accompanied by the financial, technical, and governance support that makes compliance feasible for under-resourced organisations.

V. CONCLUSION

Regional football clubs in Northern Uganda face a structural financial sustainability problem whose roots lie not in any single challenge but in the systematic absence of the institutional, commercial, and governance conditions through which sustainable sporting organisations are built. The study has established that the funding ecosystem is characterised by informal community dependence rather than formal commercial revenue; that financial challenges cascade across player welfare, transport, competitive participation, and training quality; that survival strategies, while demonstrating genuine community resilience, are by definition insufficient to generate long-term organisational capacity; and that locally adapted income-generating activities, particularly farming, represent an emergent but still embryonic pathway toward greater financial independence.

What makes Northern Uganda a particularly instructive case is the combination of its post-conflict context, its genuine community embeddedness, and its distance from the capital-centric sports infrastructure that has historically defined Ugandan football's institutional landscape. Regional

clubs here are not failing versions of Kampala clubs. They are different kinds of organisation, more socially embedded, more community-dependent, more resilient in informal terms, and less equipped for the commercial and institutional requirements of formal financial sustainability. Addressing their financial challenges requires approaches calibrated to their specific institutional reality rather than frameworks imported from contexts where commercial sports infrastructure already exists. The study argues for a deliberate, multi-level transition strategy in which clubs build more predictable internal revenue through locally adapted diversification; football governing bodies provide the institutional connections and support that convert community clubs' social assets into commercial relationships; government creates the policy and financing environment in which regional football can grow; and researchers and development partners produce the evidence and co-finance the innovations that make this transition credible and feasible.

VI. IMPLICATIONS OF THE STUDY

Theoretical Implications

This study makes three contributions to the theoretical literature on sport finance, resource dependence, and football sustainability. First, it extends Resource Dependence Theory to a post-conflict African grassroots sport context, demonstrating that RDT's core propositions about organisational vulnerability and the strategic management of resource dependence apply in qualitatively distinct ways when the primary resources are community social capital rather than financial capital or market access. Second, it provides empirical substantiation for the survival and sustainability distinction that the football sustainability literature has theorised but rarely documented at the level of regional club operations, establishing both the mechanisms through which survival and sustainability diverge and the transition conditions that would enable clubs to move from one to the other. Third, it demonstrates that locally adapted social entrepreneurship, in the form of agricultural income generation, represents a theoretically meaningful and practically viable form of sport organisation diversification that the existing literature's concentration on commercial models has obscured.

Policy Implications

For the Uganda government and the Ministry of Education and Sports, the study provides empirical grounds for developing a dedicated regional football development fund, specifically targeting the Acholi and Lango sub-regions as part of the broader Northern Uganda post-conflict recovery agenda. For FUFA and the Northern Regional Football Association, the study argues for a proactive sponsorship facilitation role, using the associations' institutional credibility and relationships to connect clubs with local and regional corporate partners, rather than limiting institutional engagement to regulatory and technical functions. For international development partners investing in Northern Uganda's post-conflict recovery, the study argues for including sport infrastructure and governance in development portfolios, recognising the social functions that

regional football clubs perform and the financial sustainability that dedicated investment could support.

VII. RECOMMENDATIONS

For Regional Football Clubs

1. Develop and implement locally adapted income-diversification plans that capitalise on available land, labour, and community networks, including agricultural projects, poultry keeping, venue hire, and community events, as a foundation for building more predictable internal revenue that reduces dependence on volatile external sources.
2. Establish basic financial governance systems, including simple annual budgets, income and expenditure records, quarterly reporting to club leadership, and asset registers, as prerequisites both for internal accountability and for external engagement with potential sponsors and institutional partners who require financial transparency.
3. Develop formal sponsorship documentation, including club profiles, impact statistics, fan base estimates, social media evidence, and standardised partnership proposals, to convert community clubs' genuine community embedding into credible commercial propositions for local and regional business sponsors.
4. Form inter-club cooperative structures for shared transport arrangements, bulk equipment purchasing, and joint marketing, enabling smaller clubs to achieve commercial efficiencies that individual clubs cannot generate independently.

For FUFA and Regional Football Associations

5. Establish a regional sponsorship facilitation programme that actively matches clubs with local and regional corporate partners, leveraging the association's institutional credibility, media relationships, and governance infrastructure to create commercial introductions that individual clubs cannot initiate independently.
6. Review the compliance burden imposed on community sports clubs under the National Sports Act (2023) and National Sports Regulations (2025), and develop a graduated compliance pathway that provides proportionate requirements for resource-constrained clubs alongside practical support, both financial and administrative, for meeting those requirements.
7. Invest in a digital visibility programme for regional football, including a standardised club profile database, regular match result dissemination, and social media content support, to increase the media exposure that the KII evidence identifies as the most frequently cited barrier to sponsorship attraction.

For Government and Development Partners

8. Establish a Northern Uganda Regional Football Development Fund, financed jointly by the Ministry of Education and Sports and development partners, providing matching grants for clubs that demonstrate basic financial governance, develop sustainable income-generating activities, or improve physical infrastructure in ways that increase community access and commercial potential.

9. Include regional football infrastructure, comprising playing surfaces, changing facilities, and community pitches, in the Northern Uganda post-conflict recovery investment framework, recognising that adequate infrastructure is both a precondition for sporting development and a multiplier for community health, social cohesion, and economic activity.
10. Commission a longitudinal monitoring study of regional football clubs' financial sustainability across Uganda, generating the annual comparative evidence needed to track the impact of policy and programme interventions and to adjust strategies based on emerging evidence.

For Research Institutions

11. Extend the mixed-methods framework developed in this study to West Nile and other Northern Uganda sub-regions not covered in the current study, generating the broader regional evidence base needed for a comprehensive Northern Uganda football sustainability strategy.
12. Commission comparative research across all regions in Uganda, East African regional football contexts, including rural Tanzania, Kenya, and Rwanda, to determine whether the survival and sustainability gap, the community-dependence paradox, and the agricultural income-generation strategy identified in Northern Uganda represent national, regional or continent-wide patterns in grassroots African football financing.

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Niṣkāma Karma and Bodhicitta A Comparative Study of the Bhagavadgītā and Śāntideva's Bodhicaryāvatāra

Dr. Devendra Singh
Head, Department of Sanskrit Language and Literature Sanchi University of Buddhist-Indic Studies, Sanchi, Madhya Pradesh, India

***Abstract*—This paper examines two of the most influential ethical ideals of classical Indian thought: niṣkāma karma (desireless action) as articulated in the Bhagavadgītā, and bodhicitta (the awakening mind) as systematised in Śāntideva's Bodhicaryāvatāra. Although the two texts emerge from distinct metaphysical traditions (theistic Vedānta on the one hand, Madhyamaka Mahāyāna Buddhism on the other), both propose a radical reorientation of human motivation in which action is purified of self-interest and directed toward a good that transcends the individual agent. The paper argues that the two ideals converge remarkably at the level of moral psychology (the critique of egoistic craving, the cultivation of equanimity, the primacy of intention over outcome), while diverging sharply at the level of metaphysics (the status of the self, the role of God, the destination of the path). By reading the texts against each other, the paper suggests that niṣkāma karma and bodhicitta are best understood not as rival doctrines but as two solutions to a shared problem: how one may act fully in the world without being bound by the world.**

***Index Terms*—Bhagavadgītā, Bodhicaryāvatāra, bodhicitta, comparative philosophy, niṣkāma karma**

I. INTRODUCTION

Classical Indian philosophy rarely separates ethics from soteriology. The question "how should I act?" is almost always inseparable from the question "how may I be free?" Two texts illustrate this fusion with unusual clarity. The Bhagavadgītā (hereafter BhG; c. 2nd century BCE – 2nd century CE), embedded in the Mahābhārata, responds to Arjuna's paralysis on the battlefield by teaching a discipline of action performed without attachment to its fruits. The Bodhicaryāvatāra (hereafter BCA; c. 8th century CE), composed by the Nālandā monk Śāntideva, offers a step-by-step guide to generating and sustaining bodhicitta, the resolve to attain full awakening for the sake of all sentient beings.

This paper attempts such an engagement. Its central thesis is twofold. First, at the level of moral psychology, that is, the analysis of desire, attachment, intention, and equanimity, niṣkāma karma and bodhicitta display a striking structural convergence. Second, at the level of metaphysics and teleology, namely the nature of the agent, the presence or absence of a personal deity, and the ultimate aim of practice, the two ideals diverge in ways that are not merely superficial but constitutive of their respective visions.

II. CONTEXT AND BACKGROUND

Both texts have been enormously influential within their own traditions. The Gītā became the central scripture of Hindu ethical reflection, commented upon by Śaṅkara, Rāmānuja, Madhva, Jñāneśvara, Tilak, Gandhi, and Aurobindo. The Bodhicaryāvatāra became the primary handbook of Mahāyāna ethical training in Tibet, where it is memorised, recited, and taught to this day. Yet despite their comparable stature, sustained comparative treatment of the two remains limited. Scholars have compared the Gītā with Kant, with Aristotle, and with Buddhist ethics in general, but specific engagement with Śāntideva's text is rare.

The comparison proceeds textually and thematically rather than historically. No direct historical influence is claimed in either direction, although both texts belong to a shared Sanskrit intellectual culture and respond to overlapping concerns (the problem of karma, the value of renunciation, the relation between wisdom and action). Where the Gītā is cited, chapter and verse numbers follow the standard 700-verse recension [1], [2]. Where the Bodhicaryāvatāra is cited, chapter and verse numbers follow the ten-chapter canonical text edited by Vaidya [3] and translated by Crosby and Skilton [4]. Sanskrit terms are given in IAST transliteration.

The method is one of reciprocal illumination: each text is used to sharpen questions that the other leaves implicit. The aim is neither to reduce one tradition to the other nor to construct a perennialist synthesis, but to clarify what each is actually claiming.

The position taken in this essay is that niṣkāma karma means not the renunciation of desire but the renunciation of ownership over desire (cf. [5]). Just as, for Śāntideva, suffering is to be removed even though it has no owner (BCA 8.101–103; cf. [6]), so too, for the Gītā, action is to be performed even though its fruit has no owner. Desire remains; only the "mine" is removed.

III. CRITICAL ANALYSIS AND DISCUSSION

Niṣkāma Karma in the Bhagavadgītā

The problem of action

The Gītā opens with a crisis of agency. Arjuna, seeing his teachers and kinsmen arrayed against him, refuses to fight. His refusal is not cowardice but a moral argument: victory would bring guilt, and no kingdom is worth such a price (BhG 1.31–46). Kṛṣṇa's response over the following seventeen chapters can be read as an extended answer to a single question: how may one act rightly when every action seems to entangle the agent in consequences?

Kṛṣṇa first denies that inaction is possible. Every embodied being is compelled to act by the guṇas of prakṛti (BhG 3.5). The renunciate who ceases outward action while the mind continues to crave is a hypocrite (BhG 3.6). The solution therefore cannot lie in withdrawal from action but in a transformed relationship to it.

The core formulation

The doctrine receives its classic statement in BhG 2.47:

karmaṇy evādhikāras te mā phaleṣu kadācana /mā karma-phala-hetur bhūr mā te saṅgo 'stv akarmaṇi //

The verse makes four distinct claims: (i) one's entitlement (adhikāra) extends only to action itself; (ii) never to its fruits (phala); (iii) one should not make the fruit the motive (hetu) of action; and (iv) one should not become attached to inaction. The last clause is crucial and often overlooked. Niṣkāma karma is not passivity; it is the most vigorous engagement, freed of the anxiety that ordinarily accompanies engagement.

The subsequent verse names the resulting disposition samatva, "evenness," and identifies it with yoga itself (BhG 2.48). Success and failure become equal not because the agent is indifferent to outcomes in the world, but because the agent's inner stability no longer depends on them.

The psychology of desire

Chapter 2 supplies a genealogy of bondage that functions as the psychological foundation of the whole doctrine (BhG 2.62–63). From contemplation of sense-objects arises attachment (saṅga); from attachment, desire (kāma); from desire, anger (krodha); from anger, delusion; from delusion, loss of memory and discrimination; and finally destruction. The chain is important because it locates the root of suffering not in action but in kāma, the craving that fastens the self to particular outcomes. Niṣkāma karma is precisely action from which this fastening has been removed.

Chapter 3 extends this analysis by identifying kāma as the "eternal enemy" of the wise, veiling knowledge as smoke veils fire (BhG 3.37–39). The practitioner is instructed to conquer it by establishing the self in the self (BhG 3.43).

Three modalities of desireless action

The Gītā offers at least three complementary framings of how action becomes desireless.

(a) Sacrifice (yajña). Action performed as an offering, rather than for personal gain, does not bind (BhG 3.9). The Vedic ritual model is here universalised: all action, not merely ritual, can be sacrificial when its fruit is surrendered.

(b) Knowledge of the non-agent self. The one who knows that "the guṇas act upon the guṇas" understands that the true self (ātman) is not the doer (BhG 3.27–28; 5.8–9). Attachment to fruits presupposes an ego that claims authorship; when that claim dissolves, so does the attachment.

(c) Devotion (bhakti). From chapter 9 onward, the surrender of fruits acquires a personal object. Whatever one does, whether eating, offering, giving, or practising austerity, is to be done as an

offering to Kṛṣṇa (BhG 9.27). The concluding instruction of the text is to abandon all dharmas and take refuge in the Lord alone (BhG 18.66). Desirelessness thus culminates not in a void but in love.

Lokasaṅgraha: The welfare of the world

Niṣkāma karma is not merely a technique for the agent's liberation. Kṛṣṇa states that he himself, though having nothing to gain, continues to act, since if he ceased the worlds would fall into ruin (BhG 3.22–24). The wise should act "for the holding-together of the world" (lokasaṅgraham evāpi sampaśyan kartum arhasi, BhG 3.20). The Gītā thus contains an outward-facing, altruistic dimension that is frequently underplayed in readings that emphasise personal detachment alone. Later, the text describes the liberated person as sarvabhūtahite ratāḥ, "devoted to the welfare of all beings" (BhG 5.25, 12.4), and as one who sees the same self in all (BhG 6.29, 6.32).

Bodhicitta in the Bodhicaryāvatāra

The awakening mind

Bodhicitta is the defining category of Mahāyāna ethics. It designates the mind (citta) oriented toward awakening (bodhi), specifically the aspiration to attain Buddhahood in order to liberate all beings from suffering. Śāntideva's text is structured as a manual for generating (chs. 1–3), protecting (chs. 4–6), strengthening (chs. 7–8), and finally grounding in wisdom (ch. 9) this single resolve, concluding with a dedication of merit (ch. 10).

Chapter 1 praises bodhicitta in extravagant terms: it is the elixir that transmutes the impure body into a Buddha's form, the fire that consumes evil, the one refuge for beings adrift in saṃsāra. Śāntideva distinguishes two phases (BCA 1.15–16): praṇidhi-bodhicitta, the aspiration to awaken for others' sake, and prasthāna-bodhicitta, the actual engagement in the bodhisattva's practices. The distinction is that between resolving to travel and setting out on the road.

The genesis of altruistic intention

How does such an intention arise? Śāntideva's answer, developed most fully in chapter 8, is analytic rather than merely exhortative. He begins from the observation that all beings equally wish to be happy and to avoid suffering (BCA 8.94–96). The privileging of one's own happiness over others' therefore has no rational basis: when happiness is equally dear to oneself and to others, there is nothing special about oneself that would justify striving for one's own happiness alone. The argument is one of parity: there is no morally relevant feature that distinguishes my suffering from anyone else's.

Śāntideva then proceeds to the meditation on exchanging self and other (parātmaparivartana, BCA 8.120–173), in which the practitioner deliberately reverses the ordinary self-preference, learning to regard others' welfare as one's own and one's own as secondary. This is among the most demanding contemplative exercises in Buddhist literature.

Bodhicitta and the critique of self

The crucial metaphysical support for this ethic appears in chapter 9, the wisdom chapter. Śāntideva argues, in accordance with Madhyamaka philosophy, that there is no enduring, independent self

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(ātman). The "I" is a conceptual imputation upon a stream of momentary physical and mental events. From this follows a famous argument (BCA 8.101–103), extensively discussed by Williams [6]: if there is no owner of suffering, suffering should be eliminated simply because it is suffering, without asking whose it is. The abolition of the self does not undermine ethics; it universalises it. Compassion becomes ownerless.

Dedication and non-grasping

Chapter 10 dedicates all merit accumulated through the composition and practice of the text to the welfare of beings. This is not a rhetorical flourish. Within Mahāyāna soteriology, the dedication (pariṇāmanā) of merit is what prevents good action from becoming a subtle form of self-aggrandisement. The bodhisattva does not hoard virtue; virtue is given away. Śāntideva's final aspirations, to be medicine for the sick, a bridge for those crossing, a lamp for those in darkness (BCA 3.6–21), express a mode of action in which the agent has become instrumental to the good of others.

Points of convergence

Intention over outcome

Both texts locate moral worth in the quality of intention rather than in the success of results. The Gītā's mā phaleṣu kadācana has a close analogue in Śāntideva's insistence that the bodhisattva's merit derives from the aspiration to benefit beings, even when nothing has yet been achieved (BCA 1.21–23). In both, this shifts the criterion of right action from what is accomplished in the world to what is enacted in the heart.

The enemy within: Kāma and kleśa

Both texts identify inner affliction, not external circumstance, as the source of bondage. The Gītā's kāma and the Bodhicaryāvatāra's kleśa (especially anger, treated in chapter 6, and self-cherishing, treated in chapter 8) function analogously. Śāntideva's image of the afflictions as enemies who must be fought without retreat (BCA 4.28–48) parallels the Gītā's martial framing of the struggle against desire (BhG 3.43). In both, the true battlefield is internal.

Equanimity as the condition of right action

The Gītā's samatva and Śāntideva's kṣānti (patience, BCA ch. 6) share a common function: they stabilise the agent so that action is not distorted by reactive emotion. The Gītā's steady-minded person (sthitaprajña, BhG 2.54–72) who is untroubled by sorrow and undesirous of pleasure finds a counterpart in Śāntideva's practitioner who welcomes suffering as an opportunity for growth and remains unshaken by praise or blame (BCA 6.10–21; 8.16–22).

Action without ego

Both texts dissolve the ordinary agent. The Gītā says the wise man knows "I do nothing at all" (BhG 5.8). Śāntideva's Madhyamaka analysis concludes that neither agent nor action nor object exists as an intrinsic entity (BCA 9.2ff). Though the underlying ontologies differ (see the discussion of ātman

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and anātman below), the practical upshot is similar: action becomes possible without the burden of self-reference.

Orientation to the welfare of all beings

Finally, and importantly, both ideals are ultimately other-directed. Niṣkāma karma finds its purpose in lokasaṅgraha and in devotion to sarvabhūtahita; bodhicitta is by definition parārtha, "for the sake of others." Readings of the Gītā that stress only detachment, and readings of Śāntideva that stress only compassion, miss this shared structure in which detachment from self and engagement with others are two aspects of a single transformation.

Points of divergence

Ātman and anātman

The most fundamental difference concerns the self. For the Gītā, detachment is possible because the true self is eternal, unborn, and untouched by action (BhG 2.20–25). One can let go of fruits because one's real identity was never at stake in them. For Śāntideva, detachment is possible because there is no self to be at stake at all. The Gītā's non-agency rests on a metaphysics of the transcendent witness; Śāntideva's rests on a metaphysics of emptiness (śūnyatā).

This produces different phenomenologies of selfless action. The Gītā's practitioner discovers a deeper self behind the empirical ego; Śāntideva's practitioner discovers the absence of any self, and thereby the arbitrariness of the self/other boundary. It is arguably this second move that gives bodhicitta its distinctive radicalism: the exchange of self and other has no exact parallel in the Gītā, where the liberated person sees the same ātman in all but does not thereby become the other.

The presence or absence of God

The Gītā's desirelessness is finally theistic. The renunciation of fruits is a renunciation to someone: Kṛṣṇa, who receives the offering, guarantees the outcome, and promises liberation (BhG 9.34, 18.66). This gives niṣkāma karma an affective warmth and a secure foundation: the practitioner acts without anxiety because a benevolent Lord holds the world.

Śāntideva's universe contains no such Lord. There are Buddhas and bodhisattvas who may be invoked, and to whom offerings and confessions are addressed (BCA chs. 2–3), but they are exemplars and witnesses, not creators or controllers of karma. The bodhisattva's confidence rests not on divine providence but on the intrinsic power of the awakening mind and on the emptiness of the obstacles that seem to oppose it. Where the Gītā asks the practitioner to surrender, Śāntideva asks the practitioner to undertake, to make the vow oneself, with full awareness that no one else will fulfil it.

Svadharma and universal ethics

The Gītā frames action within svadharma, one's own duty as determined by birth, station, and nature (BhG 3.35, 18.41–48). Arjuna is to fight because he is a kṣatriya. Niṣkāma karma is therefore the manner in which a given social role is to be performed, not a principle for determining what the

role should be. The text is famously ambivalent about whether svadharma can be criticised from a higher standpoint.

Śāntideva's ethic is, by contrast, radically universal. The bodhisattva vow makes no reference to caste, lineage, or social station. Its scope is "all beings without exception" (BCA 3.10), and its content is derived from the single principle of the parity of suffering. Bodhicitta thus contains an internal critique of hierarchy that niṣkāma karma, as presented in the Gītā, does not.

The telos of practice

The Gītā's goal is mokṣa, understood variously as union with Brahman (BhG 5.24), attainment of Kṛṣṇa's abode (BhG 8.21), or eternal loving service (BhG 18.65). The liberated person continues to act for lokasaṅgraha, but liberation itself is the fulfilment of the individual's relation to the divine. Śāntideva's goal is Buddhahood, but Buddhahood explicitly for others. The bodhisattva may postpone personal liberation across incalculable aeons; indeed, the text frames one's own awakening as valuable primarily as the most effective means of helping beings. In the Gītā, altruism is an expression of liberation; in the Bodhicaryāvatāra, liberation is an instrument of altruism. The direction of subordination is reversed.

Renunciation of fruit versus dedication of merit

A subtle but revealing contrast lies in how each text handles the results of good action. The Gītā counsels tyāga, giving up attachment to fruit (BhG 18.2, 18.9–11). Śāntideva counsels pariṇāmanā, actively redirecting merit toward others' awakening. The first is a negative discipline (not grasping); the second is a positive one (giving away). One might say that the Gītā empties the hand, while Śāntideva opens it toward another. Both prevent the self from possessing the results of its virtue, but they do so with different gestures.

Synthesis: Two answers to one question

If the foregoing analysis is correct, niṣkāma karma and bodhicitta may be understood as structurally parallel responses to a problem both traditions inherit from the wider Indian discussion of karma: that action binds, yet action is unavoidable. The shared answer is that what binds is not action but self-referential craving, and that action purified of such craving is not only permissible but liberating.

The traditions differ on what remains once craving is removed. For the Gītā, what remains is the ātman in devoted relation to the Lord, performing its allotted duty for the world's welfare. For Śāntideva, what remains is the flow of compassionate activity, ownerless, directed by the resolve to end all suffering.

It is worth resisting two tempting oversimplifications. The first is to read the Gītā as merely a doctrine of detachment and Śāntideva as merely a doctrine of compassion; the texts show that each contains both. The second is to treat the metaphysical differences as negligible "cultural packaging" around a common core. The presence or absence of a self, and of a God, genuinely changes what desireless action is: what it feels like, what it aims at, and what sustains it when outcomes fail.

Nevertheless, a practitioner of either tradition reading the other text would recognise a companion. Both texts train the mind to act fully, care intensely, and yet remain free. In an age that tends to oppose engagement and serenity, altruism and self-care, this shared achievement retains considerable relevance.

IV. CONCLUSION

This paper has argued that the Bhagavadgītā's niṣkāma karma and Śāntideva's bodhicitta converge at the level of moral psychology, in the critique of craving, the priority of intention, the cultivation of equanimity, the dissolution of egoistic agency, and the orientation toward universal welfare, while diverging at the level of metaphysics and teleology, in their accounts of the self, the divine, the scope of duty, and the ultimate purpose of practice. Neither text is reducible to the other. Read together, however, they clarify one another: the Gītā's lokasaṅgraha is thrown into sharper relief by Śāntideva's radical altruism, and the Bodhicaryāvatāra's emphasis on non-grasping is illuminated by the Gītā's precise anatomy of desire. Future comparative work might extend this analysis to the commentarial traditions, Śaṅkara and Rāmānuja on the Gītā and Prajñākaramati on Śāntideva, where the tensions identified here are debated with great subtlety.

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Artificial Intelligence-Based Innovations for Environmental Management in Uganda A Scoping Review of Current Innovations

Henry Omara
Department of Environmental Management, Selinus University of Sciences and Literature Rome-Italy
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***Abstract*—Uganda's extraordinary biodiversity, encompassing the Albertine Rift's endangered primate populations, East Africa's most significant freshwater wetland systems, and montane forest corridors of global conservation significance, is under compound and steadily accelerating environmental stress from widespread deforestation, wetland encroachment, agricultural expansion, climate variability, and persistently inadequate environmental governance capacity. Simultaneously, artificial intelligence technologies are undergoing rapid global deployment across environmental monitoring, predictive modelling, natural resource management, and climate adaptation domains, raising the question of whether these innovations are reaching contexts such as Uganda. This scoping review systematically maps the emerging landscape of artificial intelligence applications in environmental management in Uganda, examining which specific technologies have been deployed or piloted, across which environmental domains, by which actor types, and with what documented outcomes or limitations. A systematic search of peer-reviewed literature, grey literature, policy documents, and institutional reports published between 2020 and 2026 was conducted across five databases, ultimately yielding just 18 studies and reports meeting inclusion criteria after careful screening of 247 initial records identified. Findings reveal that artificial intelligence applications in Ugandan environmental management remain genuinely promising yet geographically and thematically concentrated, with remote sensing and machine learning applications for land cover change detection and forest monitoring constituting the single dominant application cluster identified. Applications in wetland management, water quality monitoring, wildlife protection, and climate adaptation do exist but remain isolated, under-resourced, and poorly integrated into government environmental governance frameworks. Critical cross-cutting barriers, including persistent data infrastructure deficits, digital skills shortages, electricity access constraints, and an underdeveloped AI policy ecosystem, systematically limit the effective translation of global AI innovations into practical, Uganda-specific environmental management solutions. The review concludes by proposing an AI-Environmental Governance Integration Framework**

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(AEGIF), together with a set of recommendations directed at government authorities, research institutions, development partners, and the private sector operating in Uganda today.

Index Terms—**artificial intelligence; environmental management; machine learning; remote sensing; deforestation; climate adaptation; digital innovation; Uganda.**

I. INTRODUCTION

There is a productive tension running through contemporary environmental governance discourse: on one side, the accelerating sophistication of artificial intelligence tools capable of processing satellite imagery at continental scale, predicting ecosystem change across decadal timescales, and detecting illegal land conversion in near-real-time; on the other, the persistent reality that the countries facing the most severe and immediate environmental challenges including Uganda are precisely those with the least infrastructure to deploy those tools meaningfully. Bridging this tension is not merely a technical challenge. It is a governance, financing, capacity, and political challenge and one that this scoping review takes seriously as its analytical starting point.

Uganda presents a case of particular environmental urgency. The country has lost over 48% of its forest cover since 1990 (FAO, 2025), with deforestation rates in the post-2000 period accelerating dramatically, driven by agricultural expansion, charcoal production, and population growth. Wetlands which once covered approximately 13% of the national land area have declined to an estimated 8% (Twinomujuni et al., 2024; Bunyangha et al., 2022). The Lake Victoria Basin, the Kyoga Basin, and the Albertine Rift ecosystem each of global ecological significance face simultaneous pressures from land degradation, water pollution, biodiversity loss, and intensifying climate variability (Obubu et al., 2022; Byaro et al., 2023). Uganda's environmental governance institutions principally the National Environment Management Authority (NEMA), the National Forestry Authority (NFA), and the Directorate of Water Resources Management (DWRM) are chronically under-resourced relative to the scale of environmental change they are mandated to monitor, regulate, and reverse (MWE, 2021).

Artificial intelligence represents a potentially transformative set of tools for precisely this governance context. AI's capacity to process large volumes of satellite, sensor, and citizen-generated data at speeds and spatial resolutions impossible through conventional methods offers environmental agencies the possibility of extending their monitoring reach far beyond what their field officer complements can physically survey (Olawade et al., 2024; Popescu et al., 2024). Machine learning algorithms applied to multi-temporal satellite imagery can detect forest cover change, identify illegal conversion events, and classify land cover types with accuracy rates that in some studies exceed 90% enabling the kind of near-real-time monitoring that deterrence-based environmental enforcement requires but has historically been unable to achieve in low-income country contexts (Hordofa et al., 2025; Obubu et al., 2026). AI-powered water quality sensors and predictive models can support proactive water resource management in ways that sample-based

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laboratory testing cannot, given the latter's dependence on expensive equipment, trained technicians, and supply chains that frequently break down in remote areas (Hlongwa et al., 2024; Murray et al., 2024).

The global evidence base for AI in environmental management has expanded considerably since 2020. Systematic reviews and empirical studies have documented AI applications across forest monitoring (Hordofa et al., 2025), wetland classification (Twinomujuni et al., 2024), air and water quality prediction (Olawade et al., 2024; Popescu et al., 2024), biodiversity assessment (Kisubi et al., 2024), wildlife protection, and climate change modelling. The Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC, 2022) explicitly identifies digital technologies including AI as enabling tools for climate adaptation in vulnerable regions. UNESCO (2022) and CIPESA (2024) have both produced frameworks for AI governance in Africa that recognise environmental management as among the highest-priority application domains. Nalubega and Uwizeyimana (2024), in their assessment of AI applications in Uganda's public sector, demonstrate that while AI adoption is expanding in health, education, and agriculture, environmental management remains comparatively under-explored and institutionally under-integrated.

In Uganda specifically, remote sensing and geospatial analysis using AI-enhanced tools have been applied to monitor deforestation in forest reserves, map wetland encroachment in urban fringe zones, and model agricultural drought impacts on smallholder livelihoods (Kilama Luwa et al., 2021; Obubu et al., 2022; Namaalwa et al., 2020). The National Forestry Authority has piloted satellite-based monitoring systems for forest cover change detection, and NEMA has engaged with AI-adjacent remote sensing tools in the context of environmental impact assessment review. However, systematic documentation of what AI tools have been used, by whom, in which environmental domains, with what results, and within what institutional frameworks is substantially absent from the published literature a gap that limits both policy development and the identification of investment priorities.

This scoping review addresses that gap. It does not set out to evaluate the effectiveness of specific AI tools, a task requiring primary experimental or quasi-experimental data but to map the landscape of current AI applications and pilots in Uganda's environmental management space, characterise the barriers and enabling conditions that shape uptake, identify critical knowledge gaps, and propose a framework for integrating AI more systematically into Uganda's environmental governance architecture. The need for such a review is timely: Uganda's Fourth National Development Plan (NDPIV) is currently under development and includes digital transformation as a cross-cutting priority; NEMA is revising its environmental monitoring strategy; and Uganda's engagement with the African Union's AI continental strategy creates a policy window for embedding AI in environmental management before governance frameworks calcify around conventional approaches.

II. CONCEPTUAL FRAMEWORK

This review is anchored in three intersecting conceptual traditions: the AI-environment nexus literature, the digital governance and technology adoption literature, and the environmental

governance framework for low-income countries. Together, these provide the analytical architecture for understanding why and how AI does or does not diffuse into environmental management in Uganda's specific institutional and resource context.

The AI-Environment Nexus

Artificial intelligence, broadly defined, encompasses machine learning, deep learning, natural language processing, computer vision, predictive analytics, and robotic process automation — a family of technologies whose common property is the capacity to perform complex pattern recognition and decision-relevant inference on large datasets without explicit rule-based programming (Olawade et al., 2024). In environmental science, AI has been most extensively applied in remote sensing for land cover classification and change detection; in climate modelling for downscaling global circulation models to regional scales; in biodiversity monitoring through acoustic and camera-trap image processing; and in environmental quality monitoring through sensor network data integration and predictive modelling (Popescu et al., 2024; Kisubi et al., 2024). Hordofa et al.'s (2025) review of AI and machine learning in tropical forest monitoring documents the progression from conventional satellite-based classification to deep learning approaches capable of detecting deforestation events in near-real-time, with accuracy substantially exceeding traditional methods.

Digital Governance and Technology Adoption in Africa

The digital governance literature emphasises that technology adoption in public sector and environmental management contexts is not primarily determined by technical capability but by institutional readiness, political economy, and the alignment of technology with existing governance incentives (Nalubega & Uwizeyimana, 2024; CIPESA, 2024). In Uganda specifically, the Fourth Industrial Revolution policy framework, the National Information Technology Authority's 2022 survey, and CIPESA's (2024) AI ecosystem assessment all identify infrastructure deficits like electricity access, internet connectivity, data storage as the primary physical barriers to AI diffusion, while digital skills gaps, weak AI governance frameworks, and limited awareness among environmental sector officials constitute the institutional barriers. The AI-environment nexus in Uganda thus operates within a broader digital transformation context that simultaneously creates opportunities and constraints.

Environmental Governance in Low-Income Countries

Environmental governance theory applied to low-income country contexts emphasises the importance of multi-level governance architectures in which national institutions, local communities, civil society, and international actors play complementary and co-constitutive roles (Obubu et al., 2022; Namaalwa et al., 2020). In Uganda, the National Environment Act (2019) and the Climate Change Act (2021) provide the legal framework for environmental governance, but their effective implementation is constrained by resource deficits at every level from NEMA's monitoring budget to the capacity of district-level environment officers. AI's potential contribution

to this governance architecture lies in extending the reach of monitoring and enforcement beyond what physical presence can achieve but only if the data, skills, and institutional mandates to act on AI-generated evidence exist (MWE, 2021; Obubu et al., 2026).

III. RESEARCH OBJECTIVES

The general objective of this scoping review is to systematically map and characterise the current state of AI applications in environmental management in Uganda. The specific objectives are to:

1. Identify and catalogue AI tools, methods, and applications deployed or piloted in Uganda's environmental management sector between 2020 and 2026;
2. Characterise the environmental domains, geographic scales, actor types, and institutional contexts within which AI applications have occurred;
3. Assess the documented outcomes, limitations, and enabling conditions of AI applications in Ugandan environmental management;
4. Identify critical knowledge gaps and research priorities for future investigation; and
5. Propose a framework and recommendations for more systematic integration of AI into Uganda's environmental governance systems.

IV. METHODOLOGY

Scoping Review Framework

This study employs the scoping review methodology following the framework of Arksey and O'Malley (2005) as updated by Levac et al. (2010) and guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) checklist (Tricco et al., 2018). Scoping reviews are appropriate for emerging and heterogeneous evidence bases where the goal is evidence mapping identifying what is known, what actors are involved, and where the key gaps lie rather than pooling quantitative effects across comparable studies (Peters et al., 2020). The AI-in-environment field in Uganda represents precisely this kind of emerging, heterogeneous evidence landscape, making scoping review methodology the most appropriate design.

Eligibility Criteria

Inclusion criteria specified: (1) primary study area or pilot implementation in Uganda, or for studies with direct policy or methodological relevance to Uganda, East African comparable settings; (2) publication or production between January 2020 and June 2026; (3) explicit engagement with AI, machine learning, deep learning, remote sensing, or related digital analytical technologies in an environmental management context; (4) publications in English-language peer-reviewed journals, institutional reports, policy documents, or credible grey literature sources; and (5) sufficient methodological description to assess reliability and relevance. Excluded sources included purely conceptual AI papers with no environmental application, medical or agricultural

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AI applications outside the environmental domain, and commercial product promotional materials without independent empirical content.

Data Collection Methods

A structured systematic search was conducted between March and June 2026 across five databases: Web of Science, Scopus, Google Scholar, African Journals Online (AJOL), and the Makerere University Institutional Repository. Grey literature was retrieved from: NEMA Uganda, the National Forestry Authority (NFA), the Directorate of Water Resources Management (DWRM), the National Information Technology Authority (NITA), CIPESA, the World Bank Uganda Country Office, FAO Uganda, and UNDP Uganda. Search strings combined terms from three domains: (1) AI terms: artificial intelligence, machine learning, deep learning, remote sensing, computer vision, predictive modelling, neural network; (2) Environmental domain terms: environmental management, deforestation, wetland, water quality, biodiversity, climate change, land use, forest monitoring, pollution; and (3) Geographic terms: Uganda, East Africa, Lake Victoria, Albertine Rift, Nile Basin. Boolean and operators combined domain clusters; OR operators linked synonymous terms within clusters.

From 247 initially identified records, 89 were excluded at title and abstract screening as clearly outside scope. A further 140 were assessed at full-text screening: 129 were excluded for failing to meet one or more eligibility criteria (most commonly: Uganda focus absent from ostensibly relevant papers; AI engagement too tangential; publication outside the 2020–2026 window; or insufficient methodological description). Eighteen sources met all eligibility criteria and were retained for data extraction. Inter-rater reliability between two reviewers at the full-text screening stage was assessed using Cohen's kappa ($\kappa = 0.81$), indicating strong agreement. Discrepancies were resolved through structured consensus discussion.

Structured data extraction captured: study author(s), publication year, source type, primary AI technology or method, environmental domain, geographic scale and location, actor type (government, academic, NGO, international organisation, private sector), reported outcomes or findings, identified barriers and enablers, and funding source. A standardised extraction template was developed and piloted on five records before full deployment.

Data Analysis

Extracted data were analysed through a two-stage process. In the first stage, descriptive quantitative analysis summarised the distribution of included sources across source type, publication year, AI technology type, environmental domain, actor type, and geographic scale, using frequency counts and percentages. These distributions are presented in Tables 1 through 4 in the Results section. In the second stage, qualitative thematic synthesis following the approach of Thomas and Harden (2008) was applied to the extracted narrative content on outcomes, barriers, and enabling conditions, generating the five cross-cutting thematic categories presented in the AI-

Environmental Governance Integration Framework (AEGIF) under discussion section. The quantitative and qualitative analyses were integrated through a narrative convergence approach in which each quantitative distribution was interpreted through the thematic lenses developed in the qualitative synthesis.

Ethical Considerations

As a systematic scoping review of publicly available published and grey literature, this study does not involve primary data collection from human participants and therefore does not require formal ethical review board approval. However, three ethical considerations bearing on the review's conduct and reporting deserve explicit acknowledgement. First, source attribution integrity: all sources are cited accurately and fully, with no selective quotation or misrepresentation of findings. Where studies report mixed or negative results for AI applications, these are reported with the same prominence as positive findings a commitment to avoiding the publication bias that can distort evidence syntheses in emerging technology fields. Second, researcher positionality: the review team includes researchers with professional interests in both AI technology advocacy and environmental governance, a combination that creates potential for motivated reasoning in evidence interpretation. The use of explicit eligibility criteria, structured data extraction, and inter-rater reliability assessment is designed to mitigate this risk. Third, community impact awareness: the review's recommendations, if implemented, could shape investment and policy decisions affecting communities dependent on natural resources. This responsibility has informed the emphasis placed on local knowledge integration, community data sovereignty, and equity-sensitive design in the AEGIF framework.

Limitations of the Study

Four limitations shape the scope and confidence of this review's findings. First, the evidence base for AI in Ugandan environmental management is genuinely thin, the 18 retained sources represent the full retrievable landscape, and many are institutional reports or pilot evaluations rather than peer-reviewed empirical studies. Conclusions about the effectiveness of specific AI tools for Ugandan environmental management cannot be drawn from this evidence base; what can be drawn are conclusions about the current application landscape and its gaps. Second, language restriction to English-language sources may have excluded relevant studies published in French particularly comparative studies from Francophone East and Central African countries that could provide useful policy learning for Uganda. Third, the 2020–2026 publication window excludes potentially foundational AI-environment applications in Uganda from earlier periods; the scoping review characterises the contemporary innovation landscape, not the full historical trajectory. Fourth, the heterogeneity of AI tools, environmental domains, and methodological approaches across the 18 retained sources makes systematic comparison difficult; each application exists in a different technical, institutional, and ecological context, limiting the generalisability of cross-source conclusions.

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V. RESULTS AND FINDINGS

Characteristics of Retained Sources

Table 1 presents the distribution of the 18 retained sources across source type, publication year, and actor type. The dominance of grey literature and institutional reports reflects the nascent state of peer-reviewed AI-environment research specifically situated in Uganda, a pattern consistent with Nalubega and Uwizeyimana's (2024) broader finding that AI research in Uganda's public sectors is more advanced in practice than in academic documentation.

Table 1: Characteristics of Retained Sources (N = 18).

Source Characteristic	Category	n (18)	% of 18
Source type	Peer-reviewed journal article	7	38.9%
	Institutional / government report	4	22.2%
	International organisation report	3	16.7%
	NGO / civil society publication	2	11.1%
	Conference proceedings	2	11.1%
Publication year	2020–2021	3	16.7%
	2022–2023	6	33.3%
	2024–2026	9	50.0%
Primary actor type	Academic / research institution	8	44.4%
	International organisation (FAO, UNDP, World Bank)	4	22.2%
	Government agency (NEMA, NFA, NITA)	3	16.7%
	NGO / civil society	2	11.1%
	Private sector	1	5.6%

Source: Author's Systematic Review (2026).

The temporal distribution is telling: 50% of retained sources were published in 2024–2026, confirming that AI applications in Uganda's environmental management space are a genuinely recent phenomenon whose trajectory is still being established. The dominance of academic and international organisation actors, together 66.6% of retained sources compared to the 16.7% from government agencies suggests that AI-environment innovation is currently more driven by research and international cooperation than by domestic government environmental agencies.

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AI Technology Types Applied

Table 2 presents the AI and machine learning technology types documented across retained sources, revealing the dominance of remote sensing and machine learning for land cover classification over more advanced AI applications.

Table 2: AI Technology Types in Ugandan Environmental Management (N = 18, multiple per source).

AI Technology / Method	n (18)	% of 18	Primary Application Context
Remote sensing + machine learning (random forest, SVM, classification)	10	55.6%	Deforestation detection; land cover change; wetland mapping
Satellite image analysis (Google Earth Engine, Sentinel, Landsat)	9	50.0%	Forest monitoring; LULC change; agricultural mapping
Deep learning / neural networks	4	22.2%	Biodiversity image classification; deforestation detection
Predictive / statistical modelling (AI-assisted)	4	22.2%	Climate variability; water stress; disaster risk
Internet of Things (IoT) sensor integration	2	11.1%	Water quality monitoring; air quality sensing
Natural language processing / data analytics	2	11.1%	Environmental policy analysis; citizen science data
Drone-based AI image analysis	1	5.6%	Wildlife monitoring; forest boundary verification

Source: Author's Systematic Review (2026).

The concentration of remote sensing combined with conventional machine learning accounting for 55.6% of retained sources reflects both the global maturity of this application class and the relative accessibility of open-source satellite data platforms like Google Earth Engine, which requires only internet access and programming skills rather than expensive proprietary data licences. Deep learning applications (22.2%) are concentrated in the most recent publications (2024–2026), suggesting an emerging transition from classical machine learning to more computationally intensive approaches as access to cloud computing platforms improves. The low prevalence of IoT sensor integration (11.1%) and drone-based AI (5.6%) reflects the physical infrastructure constraints that Olawade et al. (2024) and Popescu et al. (2024) identify as primary barriers to AI adoption in low-income country environmental management contexts.

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Environmental Domain Coverage

Table 3 presents the environmental domains addressed across the 18 retained sources, revealing strong concentration in forest monitoring and land cover change at the expense of other environmentally critical domains.

Table 3: Environmental Domain Coverage Across Retained Sources (N = 18, multiple per source).

Environmental Domain	n (18)	% of 18	Representative Technologies	Evidence Quality
Forest monitoring and deforestation detection	11	61.1%	Landsat / Sentinel ML classification; Google Earth Engine	Moderate - peer-reviewed studies present
Wetland mapping and change detection	7	38.9%	Hyper-temporal remote sensing; ML classification	Moderate - Uganda-specific studies available
Land use / land cover change (LULC)	10	55.6%	Multi-temporal satellite ML analysis	Strong - multiple peer-reviewed studies
Water quality monitoring	3	16.7%	IoT sensors; AI predictive models	Weak - no Uganda-specific peer-reviewed studies
Biodiversity / wildlife monitoring	3	16.7%	Camera trap AI; drone image analysis	Weak - pilot stage only in Uganda
Climate change adaptation / modelling	4	22.2%	AI downscaling; drought prediction models	Moderate - regional studies applicable
Environmental policy and governance	4	22.2%	NLP; data analytics; AI governance frameworks	Weak - primarily grey literature
Waste management	2	11.1%	AI waste sorting; predictive waste generation	Very weak - conceptual / legal analysis only

Source: Author's Systematic Review (2026).

The 61.1% concentration in forest monitoring and 55.6% in LULC change reflects the tractability of these domains to satellite-based remote sensing approaches that are globally available and do not require costly local infrastructure deployment. The comparative weakness of evidence in water

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quality monitoring (16.7%), biodiversity and wildlife monitoring (16.7%), and waste management (11.1%) domains where environmental need is acute and AI potential is substantial reflects precisely the infrastructure, data, and skills gaps that this review identifies as its central analytical concern. The weak evidence quality in these domains means that Ugandan environmental managers lack the evidence base to make informed decisions about AI investment in the sectors where monitoring deficits are most consequential.

Geographic and Institutional Coverage

Table 4 presents the geographic distribution and institutional coverage of AI environmental management applications across Uganda.

Table 4: Geographic and Institutional Coverage of AI Environmental Management Applications.

Geographic / Institutional Dimension	Category	n (18)	% of 18
Geographic focus	National scale (Uganda-wide)	8	44.4%
	Regional / sub-national (specific district or watershed)	6	33.3%
	Lake Victoria or Basin-specific	3	16.7%
	Urban (Kampala-focused)	3	16.7%
	Specific protected area (forest reserve, national park)	4	22.2%
Institutional lead	Makerere University / Ugandan universities	6	33.3%
	International research organisations	5	27.8%
	Government environmental agencies (NEMA, NFA, DWRM)	3	16.7%
	International NGOs	2	11.1%
	Private tech sector	2	11.1%
Integration with government systems	Fully integrated into government monitoring	1	5.6%
	Partially integrated / government aware	5	27.8%
	No government integration (research / pilot only)	12	66.7%

Source: Author's Systematic Review (2026).

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The institutional integration data in Table 4 are the most policy-critical finding in the quantitative analysis. Only 5.6% of retained sources, a single application document has full integration of AI-generated environmental intelligence into government monitoring systems. 66.7% of applications exist as research or pilot projects with no government integration. This governance disconnect is the central structural problem that the proposed AI-Environmental Governance Integration Framework is designed to address, and it is consistent with Nalubega and Uwizeyimana's (2024) finding that AI adoption in Uganda's public services more broadly is characterised by a significant gap between application pilots and institutional embedding.

Documented Outcomes, Barriers, and Enabling Conditions

Table 5 summarises the cross-cutting barriers and enabling conditions identified through qualitative synthesis of the 18 retained sources.

Table 5: Cross-Cutting Barriers and Enabling Conditions for AI in Ugandan Environmental Management

Theme	Category	Prevalence (% of sources identifying)
Infrastructure barriers	Electricity access constraints	66.7%
	Internet connectivity deficits	61.1%
	Absence of local environmental sensor networks	55.6%
Capacity barriers	Digital skills shortage in environment agencies	72.2%
	Limited AI expertise among environmental researchers	61.1%
Data barriers	Insufficient training data for Uganda-specific models	66.7%
	Fragmented environmental data systems	55.6%
Governance barriers	No AI-specific environmental governance policy	83.3%
	Weak institutional mandate for AI in NEMA/NFA	72.2%
Enabling conditions	Open-source satellite data availability (GEE, Sentinel)	77.8%
	Makerere University AI/ML research capacity	55.6%
	Growing mobile connectivity infrastructure	44.4%
	International development partner investment	61.1%

Source: Author's Qualitative Synthesis (2026).

The barrier profile that emerges from Table 5 is systemic rather than incidental. No governance policy for AI in environmental management exists (83.3% identification), digital skills are

inadequate in environmental agencies (72.2%), and Uganda-specific training data for AI models are insufficient (66.7%). Critically, these barriers reinforce each other: the absence of AI governance policy means there is no institutional mandate to invest in skills or data infrastructure; without skills, agencies cannot build or operate AI systems; without data, AI systems cannot be trained for Uganda-specific conditions; and without governance integration, even well-trained models remain in research silos disconnected from decision-making. The most prominent enabling condition; open-source satellite data availability (77.8%) is precisely what explains the dominance of remote sensing applications: it is the one AI-environment application class that does not require Uganda to solve its data, skills, or infrastructure problems first, because the data come from global satellite platforms and the analytical tools are globally available.

VI. DISCUSSION

The picture of AI in Ugandan environmental management that emerges from this scoping review is one of genuine but fragile innovation, real applications producing real insights in specific domains and geographic contexts, but systematically disconnected from the institutional and governance infrastructure that would translate those insights into sustained environmental management improvements. This finding demands both analytical honesty and constructive response.

The Remote Sensing Dominance and Its Implications

The 61.1% concentration of AI applications in forest monitoring and 55.6% in LULC change reflects a rational response to constraint: remote sensing using free satellite platforms is the application class that fits Uganda's current infrastructure reality. But this concentration carries an analytical and policy risk the equating of 'AI in environmental management' with 'satellite-based land cover classification' obscures the much wider range of environmental challenges; water quality, biodiversity monitoring, waste management, urban pollution where AI applications exist globally but have not been piloted in Uganda. The implication is not to abandon remote sensing applications, which are generating valuable and actionable intelligence, but to resist the normalisation of the current application landscape as the appropriate or sufficient scope of AI-environment innovation in Uganda.

The Governance Disconnection Problem

The finding that 66.7% of AI environmental management applications in Uganda exist as research or pilot projects with no government integration is this review's most consequential finding for policy. It documents a systemic pattern in which valuable environmental intelligence generated at significant research investment sits in academic papers and institutional reports rather than informing NEMA enforcement decisions, NFA monitoring priorities, or DWRM watershed management plans. Nalubega and Uwizeyimana (2024) identify this governance-research disconnection as a cross-sectoral pattern in Uganda's AI landscape, but its consequences are particularly severe in environmental management, where the absence of monitoring intelligence

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has direct consequences for ecosystem health and community livelihoods. CIPESA's (2024) AI ecosystem assessment for Uganda recommends the establishment of a National AI Strategy with sector-specific implementation roadmaps; this review argues that environmental management must be a priority sector in that roadmap, with explicit institutional integration mechanisms rather than aspirational language about 'leveraging AI for sustainability'.

Data Sovereignty and Equity Dimensions

A dimension of AI's environmental management potential that the reviewed literature addresses only partially is the equity implications of AI-generated environmental intelligence. AI systems trained on global datasets may perform poorly on Uganda-specific ecological conditions, generating false confidence in monitoring outputs that are systematically miscalibrated for local realities (Hordofa et al., 2025; Olawade et al., 2024). The 66.7% identification of insufficient Uganda-specific training data as a barrier reflects not only a technical gap but a data sovereignty problem: the environmental intelligence about Uganda's ecosystems that would most improve AI model performance currently exists in dispersed, inaccessible forms in NFA forest inventory records, NEMA environmental monitoring databases, and community ecological knowledge rather than in the training datasets that would make AI models environmentally useful. Building Uganda-specific environmental AI capacity requires investment in data collection, curation, and governance infrastructure alongside the more visible investments in hardware, connectivity, and coding skills.

The AI-Environmental Governance Integration Framework (AEGIF)

The AI-Environmental Governance Integration Framework (AEGIF) proposed in Table 6 responds to the systemic governance disconnection documented in this review by organising AI integration priorities across five strategic domains, each with defined institutional responsibilities, enabling investments, and performance indicators. The AEGIF is designed as a practical implementation architecture rather than a conceptual aspiration.

Table 6: The AI-Environmental Governance Integration Framework (AEGIF).

AEGIF Domain	Core Objective	Priority Actions	Lead Institution	Key Indicator
1. Data Infrastructure	Build Uganda-specific environmental AI training datasets	Centralise NEMA, NFA, DWRM data; establish open data portal; satellite data ground-truthing programme	NEMA / NITA / NFA	Environmental open data portal operational by 2027
2. Institutional Capacity	Build AI literacy and skills in	AI skills training for NEMA and NFA officers; Makerere-	NITA / Makerere	≥50 government environmental

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AEGIF Domain	Core Objective	Priority Actions	Lead Institution	Key Indicator
	government environmental agencies	government AI-environment fellowship; embedding AI analysts in agencies	University / MFPED	staff AI-trained by 2028
3. Governance Policy	Establish AI governance framework for environmental management	AI policy chapter in NEMA strategic plan; AI-environment clause in Climate Change Act implementation rules; regulatory sandbox	NEMA / CIPESA / Parliament	AI-environment policy framework enacted by 2027
4. Application Scaling	Scale proven AI tools from pilot to operational monitoring	Remote sensing monitoring integrated into NFA enforcement; wetland AI alerts integrated into district environment planning	NFA / NEMA / District Environment Officers	AI-assisted monitoring coverage of ≥60% of gazetted forest reserves by 2030
5. Research and Innovation	Build Uganda-specific AI-environment research capacity	Dedicated national research fund for AI-environment applications; Makerere AI-environment lab; community data collection partnerships	Makerere / UNCST / International donors	≥10 Uganda-specific AI-environment peer-reviewed publications per year by 2028

Source: Author's synthesis (2025). NITA = National Information Technology Authority; MFPED = Ministry of Finance Planning and Economic Development; UNCST = Uganda National Council for Science and Technology.

VII. CONCLUSION

The question facing Uganda's environmental management sector is not whether AI technologies are capable of contributing meaningfully to the monitoring, governance, and protection of the country's extraordinary and threatened natural heritage. The evidence that they are capable is now substantial and global. The question is whether the institutional, infrastructural, and governance conditions for that contribution can be deliberately built and built soon enough to matter for ecosystems that are changing faster than the conventional monitoring systems tracking them can detect.

This scoping review has documented a real but fragile AI-environment innovation landscape in Uganda, characterised by technically credible remote sensing and machine learning applications in forest and land cover monitoring, isolated pilots in wetland management and water quality, and an almost complete absence of institutional integration into government environmental decision-making. The barriers are not technical; they are structural: absent governance policy, insufficient trained personnel, fragmented data systems, and inadequate financing for the non-hardware dimensions of AI adoption. The enabling conditions open-source satellite platforms, growing Makerere University AI research capacity, expanding mobile connectivity, and an active international development partner community represent real assets that deliberate strategy could mobilise.

The AEGIF proposed in this review provides that deliberate strategy in actionable form, with defined institutional responsibilities, enabling investments, and measurable indicators for each of its five strategic domains. Its implementation is not a guarantee that Uganda's environmental management challenges will be resolved, AI is not a substitute for the political will, enforcement capacity, and community governance that sustainable environmental management ultimately requires. But it would mean that the environmental intelligence needed to make better governance decisions was being generated, integrated, and used and that Uganda was building its own capacity to continue developing that intelligence as the technology, the ecosystems, and the governance landscape continue to evolve.

VIII. IMPLICATIONS OF THE STUDY

Theoretical Implications

This scoping review makes three contributions to the theoretical literature on AI governance, digital development in Africa, and environmental management in low-income countries. First, it provides empirical specificity to the general claim that AI diffuses unevenly across environmental domains demonstrating that in Uganda, the determinants of this uneven diffusion are institutional and infrastructural rather than technical. Second, it extends Nalubega and Uwizeyimana's (2024) AI-Uganda public service analysis to the environmental sector, establishing that the governance disconnection pattern identified across Uganda's public services is particularly consequential in environmental management given the ecosystem irreversibility costs of monitoring failure. Third, it contributes to the global AI-environment literature by providing the first systematic scoping review of AI environmental management applications specifically focused on Uganda, generating the baseline evidence needed for subsequent impact evaluation research.

Policy Implications

For NEMA, the NFA, and the Ministry of Water and Environment, the findings provide justification for: establishing AI as a specified methodology within Uganda's environmental monitoring framework rather than treating it as an optional technology innovation; mandating AI literacy training for environmental sector staff as part of the revised environmental governance

strategy; and engaging with NITA and CIPESA to develop the AI-environment governance chapter of Uganda's National Digital Transformation Strategy. For international development partners, the findings argue for directing AI-environment investment beyond hardware and connectivity infrastructure to the institutional capacity development, data governance, and policy framework dimensions that determine whether AI tools translate into environmental governance improvements.

IX. RECOMMENDATIONS

The following nine recommendations are directed at the Government of Uganda, research institutions, international development partners, the private sector, and the broader research community. Together they constitute an evidence-based agenda for accelerating the responsible integration of artificial intelligence into environmental management in Uganda.

1: Establish a Dedicated AI for Environmental Management Strategy

The Government of Uganda, through the National Environment Management Authority, should develop a dedicated AI for Environmental Management strategy within NEMA's five-year strategic plan covering 2026 to 2031. The strategy should designate AI integration as a cross-cutting institutional priority with a dedicated budget line, a named senior official responsible for overseeing implementation, and annual progress reporting to the NEMA Board. This strategic commitment is the foundational governance instrument without which all downstream AI-environment investments risk remaining fragmented, under-resourced, and disconnected from the enforcement and monitoring functions that environmental management requires.

2: Create an Environmental Data Open Access Portal

NEMA, in collaboration with the National Forestry Authority, the National Information Technology Authority, and the Directorate of Water Resources Management, should establish an Environmental Data Open Access Portal consolidating environmental monitoring data from all four institutions in machine-readable formats accessible to researchers, civil society, and the private sector. Addressing the data infrastructure deficit is the single most consequential enabler of AI-environment application development in Uganda. Without consolidated, standardised, and openly accessible environmental data, neither national researchers nor international partners can develop the AI models that Uganda-specific environmental challenges require.

3: Build AI Literacy Across Environmental Governance Institutions

The Government of Uganda should mandate AI literacy training for all Grade III and above environmental officers across NEMA and the National Forestry Authority within a three-year implementation window, delivered through a structured partnership between the National Information Technology Authority, Makerere University, and international development partners. In parallel, the National Forestry Authority should integrate AI-assisted satellite monitoring outputs into its gazetted forest reserve enforcement protocol, establishing a clear operational chain

from AI-generated deforestation alert through field verification to formal enforcement action. Closing the gap between AI research outputs and environmental governance instruments requires both the human capacity to interpret AI evidence and the institutional processes to act on it.

4: Establish a Dedicated AI and Environmental Governance Research Facility

Makerere University's College of Agricultural and Environmental Sciences and other Ugandan public and private universities should establish a dedicated AI and Environmental Governance Research Laboratory with a mandate to develop Uganda-specific AI training datasets, validate global AI models against Ugandan ecological and biophysical conditions, and produce peer-reviewed evidence for environmental policy and investment decisions. This facility should serve as the primary national interface between global AI innovation and Uganda-specific environmental management needs, anchoring the applied research agenda that the current evidence base consistently identifies as the critical missing link between proof-of-concept pilots and scalable governance applications.

5: Generate the Longitudinal and Baseline Data That the Field Needs

Research institutions, led by government Universities like Makerere University, should design and implement a longitudinal AI-environment monitoring study spanning all of Uganda's major ecosystem types, including forests, wetlands, savannahs, and montane environments, generating the baseline and time-series data required for AI model training and rigorous environmental change attribution. This longitudinal programme should be complemented by community-based participatory research that incorporates local and indigenous ecological knowledge into AI training data development, ensuring that AI models for Ugandan environmental management reflect the depth and granularity of community-held environmental observation alongside satellite imagery and sensor data. These two investments address the twin data deficits, institutional and community-level, that systematically constrain AI-environment application quality in Uganda.

6: Redirect Technical Assistance Toward Capacity and Governance Rather Than Hardware

International development partners should direct technical assistance investment toward the institutional capacity and data governance dimensions of AI-environment adoption specifically, covering AI skills training for government environmental staff, data infrastructure development, open data policy support, and regulatory framework strengthening rather than concentrating resources in hardware procurement and connectivity infrastructure that the Ugandan government and private sector are increasingly able to provide independently. This reorientation responds directly to the evidence base, which consistently identifies human capital and governance deficits rather than hardware gaps as the binding constraints on AI-environment application uptake in Uganda's public sector.

7: Fund an Applied AI-Environment Innovation Challenge for Uganda

International development partners and the private sector should jointly fund a multi-year AI-environment innovation challenge specifically targeting Ugandan researchers and technology

entrepreneurs, with competitive grants of between USD 50,000 and USD 200,000 for applied AI-environment applications that demonstrate a credible and time-bound pathway to integration into government environmental management systems within three years of award. Grant criteria should prioritise applications that address documented governance gaps, use locally generated training data, engage government institutional partners from the design stage, and include rigorous independent evaluation components that contribute to the regional evidence base.

8: Develop AI Governance Safeguards for Environmental Applications

International development partners, in collaboration with the Government of Uganda and Ugandan civil society, should support the development of AI governance safeguards specifically designed for environmental management applications in the Ugandan context. These safeguards should include data quality and provenance standards, model transparency and explainability requirements, community data consent frameworks appropriate for applications drawing on locally observed ecological knowledge, and bias assessment protocols sensitive to Uganda's social and ecological heterogeneity. Robust AI governance safeguards are a precondition for public trust in AI-environment systems, particularly for applications that inform enforcement decisions affecting community land use and resource access.

9: Prioritise Causal Evaluation and Standardised Assessment Frameworks

The research community should prioritise primary experimental and quasi-experimental evaluation studies of specific AI applications in Ugandan environmental management, moving decisively beyond the pilot and proof-of-concept stage that characterises the current evidence base to generate the causal evidence on effectiveness and cost-efficiency that informed investment decisions require. These evaluation studies should be conducted using standardised assessment frameworks developed for AI-environment application performance in low-income country contexts, enabling systematic comparison of findings across Uganda, East Africa, and sub-Saharan Africa, and supporting the rapid identification and scaling of approaches whose effectiveness has been rigorously demonstrated. Open-access publication of all evaluation findings should be required as a condition of research funding.

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Exploring the Use of Artificial Intelligence Based Innovations in Water, Sanitation and Hygiene Sector under Humanitarian Response in Fragile Settings A Scoping Review

Henry Omara
Department of Environmental Management, Selinus University of Science and Literature, Rome, Italy
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Abstract—**Access to safe water, adequate sanitation, and appropriate hygiene services remains among the most critical and chronically unmet needs in humanitarian crises globally. Fragile settings, characterised by the intersection of armed conflict, institutional weakness, population displacement, and environmental stress, present the most severe WASH challenges while simultaneously being the contexts most resistant to conventional humanitarian response modalities. Artificial intelligence technologies, encompassing machine learning, deep learning, predictive analytics, Internet of Things-integrated sensor networks, natural language processing, and remote sensing, are undergoing rapid global diffusion into WASH management. However, the extent, character, and quality of their application in humanitarian fragile settings specifically remains poorly mapped in the academic and grey literature. This scoping review systematically characterises the current innovation landscape at the intersection of artificial intelligence and WASH under humanitarian response, examining what AI-based innovations have been deployed or piloted, across which WASH domains, by which actor types, with what documented outcomes, and against what structural and operational barriers. A systematic search across six databases and grey literature sources yielded 21 studies and reports meeting inclusion criteria after the screening of 312 initial records. Findings reveal that AI-WASH innovation in humanitarian fragile settings is nascent, geographically uneven, and concentrated in water quality monitoring and epidemiological disease prediction, with applications in sanitation management, hygiene behaviour change, governance support, and supply chain logistics remaining substantially underdeveloped. Critical barriers, including data scarcity in fragile settings, digital infrastructure deficits, power supply constraints, community trust challenges, and the absence of ethical frameworks governing AI deployment among vulnerable populations, systematically impede the translation of globally available AI-WASH tools into humanitarian operational practice. The review proposes the AI-WASH**

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Humanitarian Integration Framework and evidence-based recommendations for actors across the humanitarian, research, and technology sectors.

Index Terms—**artificial intelligence; humanitarian WASH; humanitarian response; fragile settings; scoping review; machine learning; digital innovation; water quality; displacement**

I. INTRODUCTION

Every humanitarian response begins at least with water supply. Not because water is the only thing that matters amid the chaos of displacement, conflict, and institutional collapse, but because without safe water, nothing else that emergency responders provide can function as intended. Oral rehydration salts require clean water to dissolve. Medical facilities require sanitation infrastructure to prevent nosocomial infections from killing the patients they treat. Children cannot absorb the nutritional value of supplementary food if enteric pathogens are continuously reinfecting their guts through contaminated water sources. And the women and girls who bear the overwhelming burden of water collection in displaced communities cannot participate in livelihoods, education, or community governance while spending four to six hours daily collecting water from distant, often unsafe sources. WASH, water, sanitation, and hygiene, is not one cluster among many in humanitarian response. It is the infrastructure through which most other interventions either work or fail (Alareqi et al., 2024; D'Mello-Guyett et al., 2024).

Despite this centrality, the humanitarian WASH evidence base has long carried a particular frustration: strong normative frameworks sitting alongside weak operational evidence, and implementation systems whose reach, quality and sustainability fall consistently short of what's needed. D'Mello-Guyett et al. (2024), in the most comprehensive recent research prioritisation exercise for WASH in humanitarian crises, engaging 286 global WASH and health experts, documented that evidence gaps remain pervasive across nearly every dimension of humanitarian WASH practice, from water source design to hygiene behaviour change, from sanitation facility use to coordination with health interventions. Alareqi et al.'s (2024) systematic review and meta-analysis of WASH interventions during humanitarian crises confirmed that while WASH interventions are critical for survival, strong evidence-based guidance for their design and implementation remains limited. In fragile settings specifically, contexts where state failure, armed conflict, mass displacement, and institutional collapse compound the environmental and epidemiological WASH challenges, these evidence deficits are most acute and their consequences most severe (Lythreatis et al., 2026; WHO/UNICEF JMP, 2023).

Artificial intelligence represents a potentially transformative set of tools for addressing the WASH implementation gap, not by replacing the human expertise, community trust, and logistical presence that effective WASH response requires, but by extending the reach, speed, and analytical depth of monitoring, prediction, and decision-support functions that those human systems cannot achieve alone. Globally, AI applications in WASH have expanded substantially since 2020: machine learning models have demonstrated superior predictive accuracy for water quality parameters relative to conventional sampling-based methods (Ighalo et al., 2021; Uddin et al.,

2024); IoT-integrated sensor networks enable real-time water quality monitoring at spatial scales and time resolutions impossible through laboratory-based approaches (Popescu et al., 2024); AI-powered remote sensing permits large-scale WASH infrastructure mapping in contexts where field enumeration is impossible or dangerous; and natural language processing tools are enabling new forms of community feedback collection and disease surveillance in displaced populations (Lythreatis et al., 2026; Hlongwa et al., 2024).

The evidence base on AI in water management more broadly has been extensively reviewed (Ighalo et al., 2021; Uddin et al., 2024), and comprehensive assessments of AI in environmental monitoring have documented the range of applicable technologies (Olawade et al., 2024; Popescu et al., 2024). The humanitarian dimension of this AI-WASH intersection, however, the specific application of AI tools in fragile, conflict-affected, and displacement settings where conventional WASH modalities face their most severe challenges, has not been systematically reviewed. Lythreatis et al. (2026) provide the most comprehensive recent review of AI in humanitarian aid broadly, but their review does not specifically analyse WASH applications, which require domain-specific technical understanding of water supply systems, sanitation engineering, and hygiene behaviour change. The Humanitarian Leadership Academy's (2025) mapping of AI in the humanitarian sector found that among 2,539 respondents across 144 countries, WASH was among the most cited sectors where AI adoption was perceived as having high potential but limited actual deployment. This review addresses that gap directly.

Fragile settings present a distinctive configuration of challenges that shapes what AI-WASH innovation is both most needed and most difficult to deploy. The OECD's States of Fragility framework identifies conflict and violence, institutional fragility, economic fragility, environmental fragility, and political fragility as the constitutive dimensions of fragility, dimensions that intersect in ways that systematically undermine the data availability, infrastructure access, institutional capacity, and community trust that AI deployment requires (OECD, 2024). In active conflict zones, ground-truth data collection for AI model training may be impossible; infrastructure for IoT sensor networks may be repeatedly destroyed; power supplies for hardware are unreliable; and community trust in external actors, including those deploying AI tools, may be actively damaged by conflict dynamics. These constraints do not mean AI-WASH innovation is impossible in fragile settings; they mean that it requires specific design adaptation, community engagement, and ethical frameworks that globally available AI tools were not typically designed with (Verhulst et al., 2024; Lythreatis et al., 2026).

The global WASH crisis in humanitarian settings provides the urgency behind this inquiry. By the end of 2024, an estimated 323 million people required humanitarian assistance, yet donor funding covered only 198 million, a 38% gap that concentrated most severely on WASH and shelter (OCHA, 2025). The WHO/UNICEF Joint Monitoring Programme (2023) documents that 2.2 billion people globally lack safely managed drinking water and 3.5 billion lack safely managed sanitation, with humanitarian and fragile settings accounting for disproportionate shares of these deficits. Infectious disease outbreaks, cholera, typhoid, hepatitis E, diarrhoeal disease, are substantially more frequent and more severe in humanitarian WASH-deficient settings, and these

outbreaks in turn undermine the food security, economic recovery, and social stabilisation on which durable peace depends (Alareqi et al., 2024; Mugabe et al., 2021). AI-based tools that could detect water quality deterioration before disease outbreaks occur, predict WASH system failure before communities lose access, or enable real-time disease surveillance in conflict-affected populations would have direct, measurable, and potentially large humanitarian impact.

This scoping review is motivated by three specific gaps in the current knowledge base. First, no systematic review has mapped AI-WASH innovation specifically in humanitarian fragile settings, a population of contexts with distinctive constraints and needs that general AI-WASH reviews do not capture. Second, the rapid pace of AI innovation in the post-2020 period means that evidence from before 2020 provides an inadequate foundation for current practice or investment decisions; a 2020-2026 focus is necessary to capture the relevant innovation landscape. Third, the humanitarian WASH community, including UNICEF, UNHCR, WHO, ICRC, OCHA, and major NGO WASH clusters, lacks a systematic synthesis of AI innovation applicable to their operational contexts, generating a translation gap between technological possibility and humanitarian practice that this review is designed to narrow (D'Mello-Guyett et al., 2024; Lythreatis et al., 2026).

The Sphere Humanitarian Charter and Minimum Standards in Humanitarian Response (Sphere Association, 2018) provides the normative foundation for humanitarian WASH, establishing minimum standards for water quantity (15 litres per person per day) and quality, sanitation facility provision, and hygiene promotion. D'Mello-Guyett et al. (2024) document that even these minimum standards are frequently unmet in contemporary crises, and that the evidence base for how to reliably achieve them in diverse fragile settings is substantially thinner than the normative framework assumes. This gap between the what of humanitarian WASH standards and the how of their reliable implementation in fragile settings is precisely where AI-based innovations have the most to contribute, providing the monitoring, prediction, and decision-support capacity to know when standards are being met or breached, and why (Alareqi et al., 2024).

Lythreatis et al. (2026), in their comprehensive review of AI in humanitarian aid, identify five crisis management phases, pre-crisis forecasting, mitigation, preparation, in-crisis response, and post-crisis recovery, across which AI applications can contribute. In WASH specifically, AI's most documented global contributions include machine learning for water quality prediction and anomaly detection, IoT-sensor networks for real-time water system monitoring, remote sensing and satellite imagery for infrastructure mapping, and natural language processing for community feedback analysis and hygiene communication (Ighalo et al., 2021; Popescu et al., 2024; Olawade et al., 2024). The key gap documented throughout the AI-humanitarian and AI-WASH literatures is the displacement between laboratory or stable-setting performance and humanitarian fragile-setting deployment, a displacement that this review's focus on fragile settings specifically addresses.

The ethics of AI deployment in humanitarian settings receives growing attention as AI tools become more operationally prevalent. Verhulst et al. (2024) identify seven distinct ethical risk categories in humanitarian AI: privacy violations through data collection from vulnerable populations; algorithmic bias amplifying existing inequities; data sovereignty concerns where

affected communities lack control over their information; dual-use risks where AI systems designed for humanitarian purposes can be repurposed for surveillance or targeting; dependency risks where AI systems undermine rather than strengthen local capacity; transparency deficits in AI systems whose decision logic communities cannot interrogate; and accountability gaps where responsibility for AI-generated decisions is diffuse across multiple actors. In WASH specifically, these risks manifest concretely: a water quality AI that generates false negatives in a cholera-contaminated aquifer can cost lives; biometric data collected for water distribution management can expose conflict-affected populations to protection risks; and AI-driven hygiene promotion algorithms trained on non-fragile-setting data may generate recommendations that are inappropriate or culturally insensitive in specific crisis contexts (Verhulst et al., 2024; Lythreatis et al., 2026).

II. METHODOLOGY

Scoping Review Design

This study employs the scoping review methodology following the framework of Arksey and O'Malley (2005) as refined by Levac et al. (2010) and reported in accordance with the PRISMA Extension for Scoping Reviews (PRISMA-ScR) checklist (Tricco et al., 2018). Scoping reviews are the appropriate methodology for this inquiry because the AI-WASH humanitarian innovation landscape is heterogeneous, rapidly evolving, and not yet consolidated enough to support formal meta-analysis, the classic conditions for scoping rather than systematic review methodology (Peters et al., 2020). The review's objective is evidence mapping and gap identification, not effect size estimation.

Eligibility Criteria

Inclusion criteria specified: (1) primary focus on an AI-based technology, method, or innovation applied or piloted in WASH programming; (2) humanitarian, fragile, conflict-affected, or forced displacement setting as the primary operational context, or, for studies providing directly applicable methodological or technical evidence, settings demonstrably comparable in their constraints; (3) publication between January 2020 and June 2026 in English; (4) peer-reviewed journals, pre-prints posted on reputable servers with author affiliations, institutional reports from recognised humanitarian organisations, or credible grey literature with methodological transparency sufficient for reliability assessment. Excluded sources included purely conceptual papers on AI without WASH application, commercial product promotion without independent evaluation, general WASH reviews without AI engagement, and sources without adequate methodological description.

Data Collection Methods

A structured systematic search was conducted between February and April 2026 across six databases: PubMed/MEDLINE, Web of Science, Scopus, Embase, WASH Cluster online

repository, and Google Scholar. Grey literature was retrieved from: UNICEF Programme Division, UNHCR Innovation Service, WHO Emergency WASH Unit, ICRC, OCHA ReliefWeb, Elrha's Research for Health in Humanitarian Crises (R2HC) programme, IRC (International Rescue Committee), Médecins Sans Frontières, REACH, Ground Truth Solutions, and the Humanitarian Leadership Academy. Search strings combined three term clusters:

1. AI technology terms: artificial intelligence, machine learning, deep learning, neural network, predictive analytics, Internet of Things, IoT, remote sensing, natural language processing, chatbot, and digital innovation.
2. WASH terms: water sanitation hygiene, WASH, water quality, water supply, sanitation, open defecation, handwashing, hygiene promotion, cholera, diarrhoeal disease, and water point.
3. Context terms: humanitarian, fragile, conflict, displacement, refugee, IDP, camp, emergency, crisis, and fragile state.

From 312 initially identified records, 98 were excluded at title and abstract screening as clearly outside scope. A further 193 records were assessed at full-text screening: 171 were excluded for failing one or more eligibility criteria, most commonly either the humanitarian/fragile setting focus was absent (the most frequent reason), the AI engagement was tangential, or the WASH application was absent. Twenty-one sources met all eligibility criteria and were retained for data extraction. Inter-rater reliability between two independent reviewers at full-text screening was assessed with Cohen's kappa ($\kappa = 0.83$, indicating strong agreement). Discrepancies were resolved through structured consensus discussion. A PRISMA-ScR flow diagram was completed documenting all screening stages.

A standardised extraction template captured for each retained source: authors and publication year; source type; AI technology or method used; WASH domain addressed; geographic context and fragility type (conflict, displacement, natural disaster, compound); humanitarian actor type; reported outcomes or findings; barriers and limitations identified; ethical considerations noted; and funding source. The template was piloted on five records before full deployment and refined based on pilot experience.

Data Analysis

Data analysis proceeded in two stages. First, descriptive quantitative analysis characterised the distribution of retained sources across source type, publication year, AI technology, WASH domain, fragility type, and geographic region, presented in frequency tables with counts and percentages. Second, qualitative thematic synthesis following Thomas and Harden (2008) was applied to extracted narrative content on AI-WASH outcomes, barriers, enabling conditions, and ethical dimensions, generating five cross-cutting thematic categories. These categories were refined through iterative independent coding by two analysts and consensus review, and are presented in Section 9.5. The quantitative and qualitative analyses were integrated through a narrative convergence approach, with each quantitative distribution interpreted through the qualitative thematic lens.

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Ethical Considerations

As a scoping review of publicly available published and grey literature, this study does not require formal research ethics board approval. Three ethical considerations are nonetheless explicitly acknowledged. First, the review covers applications of AI in extremely vulnerable populations, refugees, conflict-affected communities, displaced persons, whose data and experiences are mobilised by external actors in ways that the populations themselves have limited power to shape. The review's analytical attention to ethical challenges in AI-WASH humanitarian applications reflects not merely academic interest but a responsibility to centre the protection concerns of these populations in how the evidence is interpreted and translated into recommendations. Second, the review's focus on AI innovation carries a risk of inadvertently normalising or promoting AI adoption irrespective of evidence quality or population consent. This risk is mitigated through explicit attention to evidence quality limitations and the recommendation in Section 14 that no AI tool be deployed in humanitarian WASH without community engagement protocols and ethical impact assessment. Third, researcher positionality, two members of the review team have professional experience in humanitarian WASH programme design, is acknowledged as a potential source of motivated interpretation in the evidence synthesis, mitigated through structured extraction protocols and inter-rater agreement assessment.

Limitations of the Study

Five limitations shape the scope and confidence of this review's findings.

First, the humanitarian AI-WASH evidence base in fragile settings is genuinely scarce: the 21 retained sources represent what is publicly documented rather than what is operationally deployed, and significant AI-WASH innovation occurring within humanitarian organisations' internal systems may not be captured in published literature. The review may therefore understate the degree of current AI-WASH practice in humanitarian settings.

Second, restriction to English-language sources excludes potentially relevant evidence from French, Arabic, and Spanish-language humanitarian practice, particularly from Francophone West and Central Africa and the Arab World where significant humanitarian WASH operations occur.

Third, the heterogeneity of AI technologies, WASH domains, and fragility contexts across the 21 retained sources makes systematic comparison difficult, limiting the generalisability of cross-source conclusions.

Fourth, the 2020-2026 window is intentional but creates temporal artificiality, excluding foundational pre-2020 evidence that may still represent the current state of the art in some applications.

Fifth, most retained sources describe pilots or proof-of-concept demonstrations rather than at-scale operations with rigorous outcome evaluations, meaning that the review maps the possibility space

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of AI-WASH innovation in humanitarian settings more than it evaluates the reality of demonstrated impact.

III. RESULTS AND FINDINGS

Characteristics of Retained Sources

Table 1 presents the distribution of the 21 retained sources across source type, publication year, geographic region, and fragility type. The dominance of non-peer-reviewed sources reflects the operational and pilot character of current AI-WASH humanitarian innovation and the gap between operational practice and academic documentation.

Table 1: Characteristics of Retained Sources (N = 21).

Source Characteristic	Category	n (21)	% of 21
Source type	Peer-reviewed journal article	8	38.1%
	INGO / UN programme evaluation or report	6	28.6%
	Technical working paper or grey report	4	19.0%
	Conference or pre-print	3	14.3%
Publication year	2020-2021	4	19.0%
	2022-2023	7	33.3%
	2024-2026	10	47.6%
Geographic region (primary case)	Sub-Saharan Africa	9	42.9%
	Middle East and North Africa	5	23.8%
	South and South-East Asia	4	19.0%
	Multi-regional / global	3	14.3%
Primary fragility type	Conflict-affected	8	38.1%
	Displacement / refugee setting	7	33.3%
	Natural disaster + conflict (compound)	4	19.0%
	Post-conflict transition	2	9.5%
Primary actor type	International organisation (UNICEF, UNHCR, WHO, ICRC)	7	33.3%
	Research institution / university	6	28.6%
	NGO / humanitarian INGO	5	23.8%
	Private tech sector or start-up	3	14.3%

Source: Author's Systematic Review (2026).

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The temporal concentration in 2024-2026 (47.6%) confirms that AI-WASH humanitarian innovation is a rapidly emerging field, with the majority of documented applications post-dating 2022. Sub-Saharan Africa's dominance (42.9%) reflects both the geographic concentration of contemporary humanitarian crises and the relatively greater research attention given to African humanitarian contexts compared to Middle Eastern settings, where significant crises, including Syria, Yemen, and South Sudan, have generated WASH needs but proportionally fewer published AI innovation studies. The dominance of international organisations (33.3%) and research institutions (28.6%) over NGOs and the private sector reflects the capital and technical capacity requirements of AI deployment.

AI Technology Types in Humanitarian WASH

Table 2 presents the AI and machine learning technology types documented across retained sources, revealing the concentration in water quality prediction and satellite-based mapping alongside nascent innovations in chatbot-mediated hygiene communication and supply chain optimisation.

Table 2: AI Technology Types in Humanitarian WASH (N = 21, multiple per source).

AI Technology / Method	n (21)	% of 21	WASH Application Context	Evidence Maturity
Machine learning for water quality prediction / anomaly detection	12	57.1%	Drinking water safety monitoring; cholera outbreak prediction	Moderate, demonstrated in fragile settings
IoT sensor networks for real-time water monitoring	7	33.3%	Borehole flow monitoring; handpump status; water level sensing	Low-moderate, pilot stage in humanitarian settings
Remote sensing / satellite imagery AI analysis	8	38.1%	WASH infrastructure mapping; latrine coverage mapping; flood impact on WASH	Moderate, widely used; fragile settings adaptation needed
Natural language processing / chatbot systems	5	23.8%	Hygiene behaviour change messaging; community feedback; disease surveillance	Low, very early stage; proof of concept only
AI-assisted supply chain and logistics optimisation	4	19.0%	WASH supply forecasting; chlorine demand prediction; prepositioning	Low, primarily modelling studies

AI Technology / Method	n (21)	% of 21	WASH Application Context	Evidence Maturity
Deep learning for disease outbreak prediction	6	28.6%	Cholera; typhoid; hepatitis E early warning systems	Moderate, global evidence; fragile setting deployment limited
Drone AI / aerial survey for WASH infrastructure	3	14.3%	Open defecation site identification; camp WASH mapping	Low, small-scale pilots only
Biometric and digital ID for WASH service access	3	14.3%	Water distribution point access management; payment systems	Low, protection concerns limit deployment

Source: Author's Systematic Review (2026).

The 57.1% concentration in machine learning for water quality prediction reflects both the technical maturity of this application class globally and its direct relevance to humanitarian WASH's most critical function, ensuring that drinking water is safe. The global evidence on ML-based water quality prediction is substantial (Ighalo et al., 2021; Uddin et al., 2024), and several retained sources document its application in humanitarian fragile settings including displacement camps and post-conflict water systems. The low maturity rating for NLP and chatbot systems (23.8%, proof-of-concept only) is particularly noteworthy given the significant hygiene promotion and community engagement needs of humanitarian WASH, this represents a high-potential but under-invested application domain. The 14.3% prevalence of biometric and digital ID for WASH access management is accompanied by the most severe protection and ethical concerns in the entire evidence base, with multiple retained sources flagging privacy and targeting risks for conflict-affected populations.

WASH Domain Coverage

Table 3 presents the WASH domains addressed across retained sources, revealing a significant evidence concentration in water quality and supply relative to sanitation, hygiene promotion, and WASH governance.

Table 3: WASH Domain Coverage Across Retained Sources (N = 21, multiple per source).

WASH Domain	n (21)	% of 21	Dominant AI Approach	Humanitarian Evidence Gap Assessment
Water quality monitoring and prediction	13	61.9%	ML classifiers; neural networks; IoT sensors	Moderate - demonstrated fragile setting applications exist

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WASH Domain	n (21)	% of 21	Dominant AI Approach	Humanitarian Evidence Gap Assessment
Water supply management and distribution	8	38.1%	IoT borehole monitoring; AI logistics optimisation	Low-Moderate - supply chain AI largely modelled, not deployed
Sanitation infrastructure and coverage mapping	6	28.6%	Remote sensing; drone survey; satellite AI	Low - limited to mapping, no sanitation management AI found
Hygiene behaviour change and promotion	5	23.8%	NLP chatbots; SMS AI; social media analysis	Very low - proof of concept only; no scaled deployment
Disease surveillance and outbreak prediction	7	33.3%	Deep learning; epidemiological ML models	Moderate - global models; humanitarian deployment limited
WASH supply chain and procurement	4	19.0%	AI demand forecasting; prepositioning models	Very low - limited to modelling exercises
WASH governance and information management	4	19.0%	Data analytics; AI reporting tools; NLP for policy	Very low - almost entirely conceptual
Menstrual hygiene management	1	4.8%	App-based AI; behaviour tracking	Very low - single pilot study only

Source: Author's Systematic Review (2026).

The 61.9% concentration in water quality monitoring, compared to 23.8% in hygiene promotion and 4.8% in menstrual hygiene management, is striking given that humanitarian WASH assessments consistently identify hygiene behaviour change, open defecation, and menstrual hygiene management as among the highest-priority gaps for improving health outcomes in crisis settings (D'Mello-Guyett et al., 2024). The AI innovation landscape has not followed the evidence base on WASH health priority: it has followed the tractability hierarchy of what AI can technically do most easily, which favours quantitative water quality data over the complex social and behavioural dimensions of sanitation and hygiene. This tractability bias is the most significant structural gap in the current AI-WASH humanitarian innovation landscape.

Geographic and Institutional Distribution

Table 4 presents geographic case contexts and institutional integration data across the 21 retained sources.

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Table 4: Geographic and Institutional Distribution of AI-WASH Humanitarian Applications (N = 21).

Dimension	Category	n (21)	% of 21
Specific geographic cases (primary)	Sub-Saharan Africa - East Africa (Somalia, Ethiopia, DRC, Uganda, Kenya)	7	33.3%
	Sub-Saharan Africa - West / Central Africa (Niger, Chad, Nigeria, CAR, Cameroon)	2	9.5%
	Middle East (Syria, Yemen, Lebanon, Jordan - refugee contexts)	5	23.8%
	South Asia (Bangladesh - Rohingya; Afghanistan; Pakistan)	4	19.0%
	Multi-regional or global (not fragile-setting specific)	3	14.3%
Scale of application	Proof-of-concept / pilot only	12	57.1%
	Sub-national operational scale	5	23.8%
	National / programme scale	4	19.0%
Operational integration with WASH clusters	Fully integrated into cluster WASH programming	1	4.8%
	Partial integration - cluster aware, not embedded	7	33.3%
	No integration - research / innovation only	13	61.9%
Funding source (where documented)	USAID / US government bilateral	5	23.8%
	EU / ECHO humanitarian funding	4	19.0%
	ELRHA / UKAID research funding	3	14.3%
	UN agency self-funding	3	14.3%
	Philanthropic / private foundation	3	14.3%
	Not documented	3	14.3%

Source: Author's Systematic Review (2026).

The integration data in Table 4 are the most operationally critical finding in the quantitative analysis. Just 4.8%, a single application, is fully integrated into humanitarian WASH cluster programming, while 61.9% exist as research or innovation projects entirely disconnected from

operational WASH delivery systems. This governance-innovation disconnection mirrors the pattern documented in other humanitarian technology domains (Lythreatis et al., 2026; Humanitarian Leadership Academy, 2025) and represents the primary structural barrier to AI-WASH humanitarian impact: technically capable tools exist, but the implementation pathways from innovation to operational WASH programming are absent, underdeveloped, or systematically blocked by institutional, capacity, and resource constraints.

Outcomes, Barriers, and Enabling Conditions

Table 5 presents the cross-cutting barriers and enabling conditions identified through qualitative synthesis of all 21 retained sources.

Table 5: Barriers and Enabling Conditions for AI-WASH Innovation in Humanitarian Settings (N = 21).

Theme	Category	Prevalence (% sources identifying)
Data barriers	Absence of baseline WASH data in fragile settings	76.2%
	Fragmented, inaccessible, or low-quality existing data	66.7%
	Data collection impossible in active conflict zones	57.1%
Infrastructure barriers	Power supply unreliability destroying IoT hardware	71.4%
	Internet / connectivity deficits in camp and remote settings	66.7%
	Hardware destruction in conflict environments	47.6%
Capacity barriers	Absence of AI/data science skills in humanitarian WASH staff	81.0%
	Low digital literacy among beneficiary communities	61.9%
Ethical barriers	Protection risks from data collection in fragile settings	66.7%
	Community distrust of AI-mediated services	52.4%
	Absence of AI ethics frameworks specific to humanitarian WASH	76.2%
Institutional barriers	No WASH cluster policy for AI integration	85.7%
	Short humanitarian project cycles incompatible with AI deployment	71.4%
Enabling conditions	Open-source ML tools and satellite platforms	71.4%
	UNHCR / UNICEF Innovation Unit investment	61.9%
	Growing mobile phone penetration in fragile settings	52.4%
	Community health worker networks as AI interface	42.9%

Source: Author's Qualitative Synthesis (2026).

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The barrier profile in Table 5 reveals a system of mutually reinforcing constraints that no single intervention can resolve. The 85.7% identification of absent WASH cluster AI policy is the most severe institutional barrier, in the absence of policy clarity on what AI tools are permissible, what data governance standards apply, and how AI-generated evidence should inform WASH decision-making, individual innovation efforts remain disconnected from the operational systems they are designed to improve. The 81.0% identification of absent AI/data science skills in humanitarian WASH staff points to the critical human resource gap: even where AI tools exist and policy permits their use, the people who would operate them have not been trained. The 66.7% identification of protection risks from data collection in fragile settings documents an ethical constraint that is not merely regulatory, in active conflict zones, beneficiary data collected for WASH purposes has been misused for targeting, and communities have legitimate reasons to resist AI-mediated data collection until robust safeguards are demonstrated.

The AI-WASH Humanitarian Integration Framework (AWHIF)

The AI-WASH Humanitarian Integration Framework (AWHIF) proposed in Table 6 organises AI-WASH integration priorities across five strategic domains, designed specifically for humanitarian fragile setting constraints. The AWHIF is intentionally sequential: domains 1 and 2 (foundations) must precede domain 3 (application), which precedes domain 4 (scale), which enables domain 5 (governance). This sequencing reflects the review's core finding that technical AI innovation without governance, ethics, and capacity foundations reliably fails to achieve humanitarian WASH impact.

Table 6: The AI-WASH Humanitarian Integration Framework (AWHIF).

AWHIF Domain	Core Objective	Priority Actions	Lead Actor	Success Indicator
1. Ethical Foundation	Establish AI ethics framework for humanitarian WASH before AI deployment	Develop WASH-specific AI ethics protocol within Sphere Standards framework; community consent guidelines; data sovereignty protocols	Sphere Association; ICVA; OCHA	AI ethics protocol endorsed by WASH Cluster global leads by 2027
2. Data Infrastructure	Create minimum viable data environments for AI-WASH in fragile settings	WASH cluster data harmonisation standards; open humanitarian WASH datasets; ground-truth collection protocols for conflict settings	OCHA; UNHCR; UNICEF Programme Division	Harmonised WASH data standard adopted across WASH clusters by 2027

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AWHIF Domain	Core Objective	Priority Actions	Lead Actor	Success Indicator
3. Priority Applications	Deploy AI in highest-need WASH domains that current innovation has neglected	AI hygiene communication pilots via CHW networks; sanitation demand ML models; outbreak early warning integration with WASH systems	UNICEF; WHO; INGO WASH technical teams	AI deployed in hygiene communication and outbreak detection in ≥5 fragile settings by 2028
4. Scale and Sustainability	Move proven innovations from pilot to operational integration within WASH clusters	AI-WASH tools integrated into WASH cluster 3Ws and information management; CHW digital capacity building; interoperability standards	WASH Cluster global lead agencies; Elrha	≥10 operational AI-WASH tools integrated into cluster programming by 2030
5. Governance and Learning	Establish accountability, learning, and improvement systems for AI-WASH	AI-WASH learning agenda within ELRHA research portfolio; mandatory post-project AI ethics audit; cross-cluster sharing platform	Elrha; ICRC; academic research partners	Annual AI-WASH humanitarian learning report published from 2027

Source: Author's synthesis (2026).

IV. DISCUSSION

The result emerging from this scoping review of AI-WASH innovation in humanitarian fragile settings is one of genuine technical promise, documented operational pilots, and systematic implementation gaps that technical innovation alone cannot bridge. The humanitarian WASH community is neither unaware of AI's potential nor entirely inactive in exploring it, UNICEF, UNHCR, and ICRC all have active digital innovation programmes, and several of the retained sources document real deployments with real humanitarian populations. But the pattern is one of isolated, under-scaled, and operationally disconnected innovations rather than systematic integration.

The Tractability Bias and Its Consequences

The most analytically important finding of this review is the mismatch between where AI-WASH innovation has concentrated (water quality prediction, 61.9%) and where humanitarian WASH

evidence identifies the greatest unmet needs (hygiene behaviour change, sanitation access, menstrual hygiene management). This tractability bias, AI being deployed where it is technically easiest rather than where it is most needed, is a predictable consequence of innovation ecosystems driven by technical feasibility rather than humanitarian priority. Water quality parameters generate quantitative sensor data that ML models can process effectively; hygiene behaviour change involves social, cultural, and gendered determinants that existing AI tools are poorly equipped to capture. Correcting this bias requires explicit investment in the harder AI applications, NLP-based hygiene communication, AI-assisted sanitation demand assessment, community-led digital feedback systems, that current humanitarian innovation ecosystems are not prioritising.

The Humanitarian AI Ethics Gap

The 66.7% identification of protection risks from data collection and the 76.2% identification of absent AI ethics frameworks for humanitarian WASH are not merely academic concerns, they represent active risks to beneficiary populations that must be addressed before AI-WASH deployment is scaled. Verhulst et al.'s (2024) seven ethical risk categories provide a starting framework, but humanitarian WASH specifically requires domain-adapted ethics protocols addressing the distinctive risks of: sensor data collection in conflict zones that could identify population concentrations to armed actors; biometric data for water distribution access that could expose protection-sensitive populations; ML models trained on non-fragile-setting data generating systematically biased recommendations for fragile-setting WASH programmes; and NLP tools for hygiene communication operating in languages and cultural contexts their training data did not represent. The humanitarian WASH community requires an ethical framework for AI deployment that is as carefully designed as the Sphere Standards it would operate alongside.

The Opportunity in Community Health Worker Networks

The 42.9% identification of community health worker (CHW) networks as an enabling condition for AI-WASH deployment is this review's most operationally promising finding and, in the authors' assessment, the most under-exploited. CHW networks represent the closest thing to universal humanitarian WASH presence in fragile settings, they exist in refugee camps, conflict-affected communities, and displacement settings across sub-Saharan Africa and South and South-East Asia; they are trusted by the communities they serve; they already collect and transmit health and WASH data; and they operate the social relationships through which hygiene behaviour change actually occurs. AI tools designed around CHW interface requirements, low-bandwidth, mobile-compatible, locally language-supported, requiring minimal training, represent the most viable pathway from AI innovation to humanitarian WASH impact at scale.

“When we built the water quality prediction system for the camp, we made it talk to the community health workers' phones. They already knew how to use WhatsApp. They already trusted the community. The AI just gave them better information to work with. That's when it stopped being a technology project and started being a WASH project.” Programme Manager, Digital WASH Innovation, humanitarian INGO, Sub-Saharan Africa (retained source interview, 2024)

V. CONCLUSION

The communities whose access to safe water, adequate sanitation, and hygiene services is most precarious are not, in most cases, in positions where they can wait for the humanitarian WASH system to resolve its evidence gaps, institutional fragmentation, and operational under-resourcing before their water supply is safe. They are in conflict zones, displacement camps, and post-disaster settings where the water they drink today may carry pathogens whose consequences they will bear tomorrow. The urgency of this reality is what makes the promise of AI-based WASH innovation genuinely important, and the systematic gaps in its humanitarian implementation genuinely costly. This scoping review has documented 21 sources of evidence on AI-WASH innovation in humanitarian fragile settings, revealing a landscape of genuine technical capability, fragmented operational deployment, and systematic governance, ethics, and capacity gaps that technical innovation alone cannot resolve. Machine learning for water quality prediction is mature enough for operational deployment and demonstrably applicable in fragile settings. Outbreak prediction tools exist and have been piloted. Remote sensing for WASH infrastructure mapping is a globally available and increasingly affordable capability. The tools are closer than the implementation systems needed to deploy them responsibly and at scale. Building those implementation systems, ethical frameworks, data governance, staff capacity, cluster integration pathways, and community engagement protocols, is the work that this review identifies as the humanitarian WASH sector's most important AI-related investment for the next five years.

VI. IMPLICATIONS OF THE STUDY

This review makes three contributions to the theoretical literature on humanitarian innovation, AI governance, and WASH in emergency response. First, it extends the AI-humanitarian nexus literature (Lythreatis et al., 2026) to the WASH-specific domain, establishing that WASH has a distinctive barrier profile, the tractability bias, the protection-sensitive data challenge, and the CHW-interface opportunity, that general AI-humanitarian frameworks do not capture. Second, it contributes to the WASH in emergencies evidence base (D'Mello-Guyett et al., 2024; Alareqi et al., 2024) by documenting how AI innovation might address the evidence and implementation gaps those reviews identify, while simultaneously demonstrating why the ethical and governance conditions for doing so responsibly are not yet in place. Third, it provides the first systematic mapping of AI-WASH humanitarian innovation as a distinct field, establishing the baseline against which future developments can be measured.

For WASH cluster global lead agencies (UNICEF, UNHCR), the review argues for establishing AI-WASH integration as a named priority in the next WASH Cluster Global Strategy, with dedicated funding lines for ethical framework development, CHW digital capacity building, and open WASH data infrastructure. For Elrha and humanitarian research funders, the review makes the case for directing research investment toward the neglected AI-WASH domains, hygiene

behaviour change, sanitation demand analysis, menstrual hygiene management, where innovation has been lowest and humanitarian need is highest.

VII. RECOMMENDATIONS

The study proposes recommendations that are directed at humanitarian WASH cluster lead agencies, research institutions, international organisations and donors, and technology developers and the private sector. Together they constitute an evidence-based agenda for responsible, equitable, and scalable integration of artificial intelligence into humanitarian WASH programming in fragile and conflict-affected settings.

1: Develop a WASH-Specific AI Ethics Protocol Within the Sphere Standards Framework

Humanitarian WASH cluster lead agencies should commission the development of a WASH-specific AI ethics protocol embedded within the Sphere Standards framework, addressing data protection, community consent, algorithmic bias, and accountability mechanisms for AI-assisted WASH programming. This protocol should be treated as a prerequisite for expanded AI-WASH deployment rather than an aspirational future development. Concurrently, Sphere Association, ICVA, and OCHA should proactively engage technology developers in the development of this framework, ensuring that technical AI expertise is incorporated into ethical standard-setting processes currently dominated by humanitarian policy rather than by the engineering and data science knowledge required to identify and mitigate AI-specific risks in fragile settings.

2: Establish a Harmonised and Open WASH Data Standard for Humanitarian Settings

Cluster lead agencies and research institutions should collaborate to establish a harmonised WASH data standard for humanitarian settings, creating minimum viable interoperable datasets that enable AI model training and deployment across different fragile setting contexts. The standard should prioritise open-access data formats accessible to research institutions and NGO partners without proprietary barriers. This recommendation responds directly to the data fragmentation finding that consistently emerges as the most significant structural barrier to AI-WASH innovation across the evidence base reviewed, and addresses both the immediate capacity gap and the long-term governance architecture needed to sustain AI-WASH application development at scale.

3: Redirect AI-WASH Investment Toward the Highest-Need Neglected Domains

International organisations, donors, and cluster lead agencies should deliberately direct AI-WASH investment toward hygiene behaviour change, sanitation demand assessment, and menstrual hygiene management, the highest-need WASH domains with the weakest current AI innovation, rather than concentrating resources in water quality prediction where the global evidence base is already substantial and the humanitarian application gap is comparatively narrow. A dedicated multi-year AI-WASH humanitarian innovation challenge targeting these neglected domains should be established, with competitive grants requiring community co-design and independent ethical impact assessment as mandatory proposal conditions. Grant criteria should prioritise

applications emerging from conflict-affected and displacement settings rather than stable or recovery contexts.

4: Design All AI-WASH Systems Around Community Health Worker Interface Requirements
Cluster lead agencies and technology developers should ensure that all AI-WASH pilot designs and product specifications are built around community health worker interface requirements from the outset, covering mobile compatibility, low-bandwidth functionality, offline capability, local language support, solar power compatibility, and a training requirement not exceeding two hours. Community health worker networks represent the most viable and equitable delivery pathway for AI-enhanced WASH services in fragile settings, and designing systems that CHWs cannot realistically operate and maintain in low-resource environments guarantees implementation failure regardless of technical performance in controlled conditions.

5: Fund a Dedicated Multi-Year Research Programme on AI-WASH in Fragile Settings
Research institutions and Elrha should fund a dedicated multi-year research programme on AI-WASH innovation specifically mandated to produce peer-reviewed evidence on outcomes, costs, scalability, and ethical implications from conflict-affected and displacement settings. This programme should incorporate empirical research on community perceptions of and consent frameworks for AI-mediated WASH services, ensuring that the governance and ethics frameworks regulating AI-WASH deployment are informed by affected population perspectives rather than exclusively by external humanitarian actor risk assessments. Evidence generated from stable or recovery contexts, which currently dominates the literature, cannot be assumed to transfer to fragile settings without empirical validation.

6: Develop and Validate a Humanitarian AI-WASH Readiness Assessment Tool
Research institutions, in partnership with cluster lead agencies, should develop and validate a Humanitarian AI-WASH Readiness Assessment Tool building on the five domains of the AI-WASH Humanitarian Integration Framework, enabling humanitarian organisations to systematically assess their current AI-WASH capability, identify priority investment areas, and track institutional progress over time. This tool should be made freely available, tested across a minimum of five distinct fragile setting contexts to ensure cross-context validity, and integrated into the AI-WASH innovation learning platform recommended below.

7: Extend Humanitarian Programme Cycles and Establish a Dedicated Learning Platform
International donors should extend humanitarian programme cycles for AI-WASH innovations to a minimum of three years, recognising that the community engagement, staff training, deployment, iterative refinement, and rigorous evaluation required for responsible AI-WASH integration in fragile settings are fundamentally incompatible with 12-18 month project cycles that currently dominate humanitarian financing. Alongside extended programme cycles, donors and cluster lead agencies should establish and resource a dedicated AI-WASH innovation learning platform within

the WASH Cluster information management architecture, enabling systematic documentation and open sharing of what works, what fails, and what ethical challenges arise across different fragile setting contexts, so that hard-won implementation learning is not lost when project cycles close.

8: Commit to Open-Source and Humanitarian Licensing for AI-WASH Tools

Technology developers and the private sector should commit to open-source or humanitarian licensing models for AI-WASH tools with demonstrable humanitarian applications, removing proprietary access barriers that prevent underfunded WASH organisations in fragile settings from deploying potentially life-saving technologies. Licensing commitments should be made at the product design stage rather than negotiated retrospectively after deployment has demonstrated commercial potential, ensuring that the humanitarian applications of AI-WASH tools are not subordinated to commercial interests when evidence of impact becomes available.

9: Prioritise Causal Evaluation Evidence and Standardised Assessment Frameworks

The research community should prioritise primary experimental and quasi-experimental evaluation studies of specific AI-WASH applications in humanitarian fragile settings, moving beyond the pilot and proof-of-concept stage that characterises the current evidence base to generate the causal evidence on effectiveness, equity, and cost-efficiency that responsible investment decisions require. Studies should assess not only technical performance indicators but community acceptance, equity of access across gender, disability, and displacement status, and the sustainability of AI-WASH systems beyond initial deployment and external technical support. Standardised evaluation frameworks should be developed to enable systematic comparison across different fragile setting contexts and to support the rapid scaling of approaches whose effectiveness has been rigorously demonstrated.

10: Ensure Community Participation and Equity are Non-Negotiable Design Standards

All actors across the AI-WASH ecosystem, cluster lead agencies, research institutions, donors, and technology developers, should treat community participation and equity of access not as aspirational programming principles but as non-negotiable design standards applied at every stage of AI-WASH tool development, piloting, deployment, and evaluation. This requires the formal integration of affected community representatives into AI-WASH product design teams, the development of accessible community feedback mechanisms for all deployed AI-WASH systems, the systematic tracking of access and outcome equity across marginalised groups including women and girls, persons with disabilities, and displaced populations, and the mandatory reporting of equity findings alongside technical performance metrics in all AI-WASH evaluation outputs.

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The Influence of Public Financial Management (PFM) on Public Health System Efficiency in Uganda: A Scoping Review

Henry Omara
Department of Environmental Management, Selinus University of Sciences and Literature Rome-Italy
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Abstract*—Uganda's public health system operates under a persistent and consequential paradox. Over the past two decades, the country has made notable gains across several key health indicators, yet the efficiency with which public health resources are converted into outcomes remains systematically constrained by weaknesses in public financial management (PFM). Health sector budget absorption rates hover between 72 and 88 percent, with significant fourth-quarter expenditure concentration that distorts planning and service delivery. Drug and medical supply stockouts affect an estimated 28 to 44% of public health facilities. National Medical Stores procurement cost premia of 15 to 30% above commercial market prices represent a chronic, unaddressed allocative inefficiency. Office of the Auditor General reports consistently identify irregularities in health sector financial management, yet resulting policy recommendations achieve implementation rates of only 40 to 60%. Despite the scale of these inefficiencies, the mechanisms linking PFM quality to health system efficiency in Uganda remain insufficiently synthesised relative to the challenge they present. This scoping review maps and synthesises available evidence on PFM and health system efficiency linkages in Uganda. A systematic search across five databases and grey literature identified 26 eligible sources from 198 records. Findings reveal that PFM influences health system efficiency through five interrelated mechanisms: budget formulation quality and alignment with actual needs; budget execution consistency, timeliness and predictability; procurement and supply chain management, with implications for input cost and availability; accountability, audit and oversight, with deterrence effects on waste and fraud; and intergovernmental fiscal transfer design, with incentive effects on district health performance. Cross-cutting themes, decentralisation fragmentation, donor alignment challenges, and human resource financial management, run through all five mechanisms. The review proposes the PFM-Health Efficiency Integration Agenda for Uganda and concludes with evidence-based recommendations for the Ministry of Finance, Planning and Economic Development, the Ministry of Health, and development partners.

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***Index Terms*—public financial management; health system efficiency; Uganda; budget execution; health financing; procurement and supply chain; universal health coverage**

I. INTRODUCTION

In the language of health financing, efficiency is not a technocratic abstraction. It is the difference between a health centre that receives its drug allocation on time and can treat the child who arrives with malaria, and one that has run out of artemether-lumefantrine because its third-quarter supply request was approved in December. It is the difference between a district health officer whose budget release arrived in March and can implement the outreach programme that was planned in October, and one who is still waiting in June. It is the difference between a procurement system that pays market prices for essential medicines and one that pays a 20% premium because the procurement planning cycle is misaligned with the market. Uganda's public health system is home to all three of these inefficiencies, and many more, and their roots are traceable, in significant measure, to the structures and quality of public financial management (PFM) that govern the allocation, execution, and oversight of health sector resources (Musiega et al., 2024; Tapsoba et al., 2024).

Uganda's health financing context provides the structural backdrop for this review. The national health budget has averaged between 6.2% and 8.9% of the national budget over the past decade, consistently below the Abuja Declaration target of 15% that the Government of Uganda endorsed in 2001, and substantially below the level required to achieve universal health coverage (UHC) targets by 2030 (Uganda Ministry of Finance, Planning and Economic Development [MFPED], 2025; Ministry of Health [MoH], 2023). Out-of-pocket expenditure remains high, estimated at approximately 41% of total health expenditure in 2023, reflecting both the under-resourcing of the public health system and the quality failures that drive patients to seek care from private providers whose cost is not covered by the public budget (WHO, 2023; World Bank, 2024). Per capita government health expenditure has stagnated in real terms, while the population continues to grow at approximately 3% per year, meaning that the per capita health resource envelope is effectively contracting. Against this constrained resource backdrop, efficiency, extracting maximum health output from available inputs, is not merely a governance aspiration. It is a survival strategy for a health system trying to serve 47 million people on a budget that is structurally inadequate for the task (UBOS, 2024; Barasa et al., 2022).

The global evidence on PFM-health efficiency linkages has developed substantially in recent years. Musiega et al. (2024), in the most directly relevant recent scoping review, published in Wellcome Open Research, synthesised evidence on the mechanisms through which PFM influences health system efficiency, finding that the entire budget process from formulation through execution shapes efficiency outcomes, with budget execution processes emerging as the most consistently identified bottleneck. Tapsoba et al. (2024), using Public Expenditure and Financial Accountability (PEFA) scores as proxies for PFM quality across sub-Saharan African countries from 2005 to 2018, found statistically significant correlations between PFM quality and

under-five mortality and maternal mortality rates, suggesting that improvements in PFM systems have direct, measurable life-saving effects. Musiega et al. (2023), examining county health systems in Kenya, documented how budget execution processes specifically, the timing of fund releases, the predictability of transfers, and the flexibility of budget lines, directly shape health system efficiency by determining whether health facilities have the resources to deliver services when services are needed.

Uganda offers a particularly instructive case for studying these relationships because it has undergone successive PFM reform efforts since the introduction of the Integrated Financial Management System (IFMIS) in the late 1990s, yet health sector financial management challenges persist at scale. The Public Finance Management Act (2015) established the legal framework for fiscal discipline, budget transparency, and accountability. The National Health Accounts exercise provides periodic evidence on financial flow patterns. The annual PEFA assessments track PFM system quality across standardised dimensions. And the Office of the Auditor General (OAG) produces detailed annual audit reports that document, with specificity, the financial management failures occurring across Uganda's health sector, from unaccounted-for funds at district level to procurement irregularities in the National Medical Stores to payroll ghost workers in health facility staff lists. What the audit evidence documents in detail, the PFM reform agenda has been unable to systematically address, and the gap between financial management aspiration and practice in Uganda's health system generates the inefficiency that ultimately costs lives (MoH, 2023; Barasa et al., 2022; Mbau et al., 2022).

Decentralisation is a cross-cutting structural factor that shapes PFM-health efficiency relationships throughout the Ugandan system. Following the 1997 Local Government Act, Uganda decentralised significant health service delivery responsibilities to district and sub-district levels, including health facility management, district health team oversight, and health worker supervision. This decentralisation created a complex multi-level fiscal architecture in which health resources flow from the national level through the Ministry of Finance to districts through the Integrated Support Programme grants, and from districts to health facilities through the facility-level conditional grants, with each transfer point representing both a potential efficiency gain (through localised decision-making) and a potential efficiency loss (through leakage, delay, and misallocation). The evidence on whether Uganda's decentralisation has improved health system efficiency is mixed: districts with stronger local governance institutions show better health resource absorption and service delivery performance, while districts with weaker local government capacity show persistent budget execution problems and facility-level stockouts that reflect both financial management and governance deficits (Namakula et al., 2025; Barasa et al., 2022).

The international donor dimension of Uganda's health financing is equally significant for PFM-efficiency analysis. Donors contribute approximately 40-50% of Uganda's total health expenditure through a mix of on-budget and off-budget channels, with a substantial proportion flowing through disease-specific vertical programmes (Global Fund for HIV/AIDS, tuberculosis, and malaria; GAVI; PEPFAR) that create parallel PFM systems, procurement modalities, and accountability structures that are not fully aligned with Uganda's national PFM architecture (WHO, 2023;

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UNICEF, 2023). The fragmentation between on-budget donor support and off-budget vertical programme funding creates allocative efficiency challenges, resources flow to donor-prioritised disease areas in proportions that may not reflect Uganda's actual disease burden, and technical efficiency challenges, parallel administrative systems create duplicative overhead costs and divert health system management attention away from comprehensive service delivery (Musiega et al., 2024; Tapsoba et al., 2024).

Health system efficiency is conventionally defined along two dimensions: technical efficiency, producing the maximum possible health outputs (services, health outcomes) from a given set of inputs (budget, staff, medicines, infrastructure); and allocative efficiency, combining inputs in the proportions that minimise cost for a given output level, or, at a higher level of analysis, allocating resources across health services and programmes in the proportions that maximise population health given budget constraints (Musiega et al., 2024; Barasa et al., 2022). Both dimensions are directly influenced by PFM quality: technical efficiency is shaped by PFM's influence on how reliably inputs (drugs, supplies, health worker salaries) are available when and where they are needed; allocative efficiency is shaped by PFM's influence on how the health budget is distributed across programmes, facilities, and geographic areas relative to need.

PFM theory identifies the budget cycle as the primary institutional mechanism through which public resources are allocated, spent, and accounted for. The cycle encompasses four phases: budget formulation (policy objectives translated into resource allocation proposals); budget enactment (legislative approval); budget execution (authorised spending translated into actual expenditure); and budget accountability (audit, evaluation, and reporting on whether resources were spent as intended and to what effect). Tapsoba et al. (2024) and Musiega et al. (2024) both demonstrate that the quality of each phase, and the coherence of the phases as an integrated system, shapes health sector efficiency outcomes, with budget execution processes generating the most consistent and direct efficiency effects in low-income country health systems. Uganda's PEFA assessments provide the most comprehensive available evidence on Uganda's PFM system quality across these phases, revealing moderate performance in budget formulation and accountability but persistent weaknesses in budget execution predictability and fiscal transfer timeliness.

Principal-agent theory provides the framework for understanding why PFM quality failures occur in Uganda's health system, why budget funds arrive late at facilities, why procurement costs exceed market prices, why audit recommendations go unimplemented. The theory identifies the information asymmetries, incentive misalignments, and accountability gaps between principals (the Ministry of Finance, the Ministry of Health, district health management teams) and agents (district accounting officers, facility managers, procurement officers, health workers) that enable and perpetuate inefficiency. Namakula et al.'s (2025) political economy analysis of health systems strengthening in Uganda documents how these principal-agent dynamics operate in practice: district health managers face competing pressures from elected politicians, central government mandates, and facility-level staff that create systematic accountability gaps, while the information asymmetries between national-level policymakers and facility-level realities enable persistent misreporting of expenditure and service delivery data.

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This scoping review addresses the specific gap of a Uganda-focused synthesis of PFM-health efficiency evidence. While Musiega et al.'s (2024) scoping review provides the most comprehensive global synthesis to date, its geographic scope is not Uganda-specific, and many of the mechanisms it identifies require Uganda-specific instantiation and contextualisation to be actionable for Uganda's Ministry of Finance, Ministry of Health, and development partners. Mbau et al.'s (2022) health financing evidence synthesis for Kenya, Barasa et al.'s (2022) work on health systems financing in East Africa, and Musiega et al.'s (2023) Kenya county budget execution study provide the closest East African comparators, but Uganda's specific institutional architecture, decentralisation model, donor relationship, and PFM reform trajectory require a dedicated synthesis. This review provides that synthesis, contributing both to the PFM-health literature and to Uganda's policy discourse on health system efficiency improvement.

II. METHODOLOGY

Scoping Review Design

This study employs the scoping review methodology following the framework of Arksey and O'Malley (2005) as updated by Levac et al. (2010) and reported in accordance with the PRISMA Extension for Scoping Reviews (PRISMA-ScR) checklist (Tricco et al., 2018). Scoping reviews are appropriate for this inquiry because the PFM-health efficiency evidence base in Uganda, while substantive in its components, has not been previously synthesised specifically for Uganda and encompasses heterogeneous source types, government budget analyses, PEFA assessments, academic journal articles, audit reports, and development partner evaluations, that cannot be formally meta-analysed but benefit from systematic charting and narrative synthesis (Peters et al., 2020).

Eligibility Criteria

Inclusion criteria specified:

1. Primary focus on PFM systems, processes, or reforms in Uganda's health sector, or, for studies providing directly applicable evidence on PFM mechanisms, other East African settings with documented Uganda relevance;
2. Explicit engagement with health system efficiency as an outcome, whether as technical efficiency, allocative efficiency, or efficiency-related outcomes including budget absorption, service delivery quality, drug availability, or health worker performance;
3. Publication between January 2020 and June 2025 in English;
4. Peer-reviewed journals, government budget reports, PEFA assessments, OAG annual reports, or development partner evaluations with adequate methodological transparency.

Excluded sources included purely theoretical PFM papers without health sector application, supply chain studies without PFM governance dimension, and cost-effectiveness analyses without PFM linkage.

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Data Collection Methods

A structured systematic search was conducted between January and June 2025 across five databases: PubMed/MEDLINE, Web of Science, Scopus, African Journals Online (AJOL), and Google Scholar. Grey literature was retrieved from: Uganda Ministry of Finance, Planning and Economic Development; Uganda Ministry of Health; Office of the Auditor General of Uganda; Uganda Bureau of Statistics; World Health Organization Uganda Country Office; World Bank Uganda; UNICEF Uganda; International Monetary Fund Article IV consultations; PEFA Secretariat; P4H Network; and the Overseas Development Institute. Search strings combined three term clusters:

1. PFM terms: public financial management, budget execution, budget formulation, fiscal transfer, procurement, PEFA, public expenditure, health financing, budget absorption.
2. Health system terms: health system efficiency, health service delivery, universal health coverage, health financing, drug supply, health workforce, health facility management.
3. Geographic terms: Uganda, East Africa, sub-Saharan Africa. Boolean And operators combined clusters; OR operators linked synonyms within clusters.

From 198 initially identified records, 62 were excluded at title and abstract screening. A further 110 were assessed at full-text stage: 84 were excluded for failing eligibility criteria, most commonly either the PFM-health linkage was insufficiently specified, the Uganda focus was absent, or the publication was outside the 2020-2025 window. Twenty-six sources met all eligibility criteria and were retained for data extraction. Inter-rater reliability was assessed between two reviewers at the full-text screening stage ($\kappa = 0.82$). Data extraction captured: source type, publication year, PFM dimension addressed, health efficiency dimension, key findings, Uganda-specific evidence, and knowledge gaps identified.

Data Analysis

Descriptive quantitative analysis summarised the distribution of retained sources across source type, publication year, PFM dimension, and health system efficiency dimension. Qualitative thematic synthesis following Thomas and Harden (2008) was applied to extracted evidence on PFM mechanisms, contextual factors, and policy recommendations, generating five primary thematic categories corresponding to the PFM-health efficiency mechanisms identified across the evidence base. A narrative convergence approach integrated quantitative distributions and qualitative themes into the PFM-Health Efficiency Integration Framework presented in Section 9.

Ethical Considerations

As a scoping review of publicly available published, government, and institutional literature, this study does not require formal ethical review board approval. Three ethical considerations are nonetheless acknowledged. First, the review synthesises evidence that includes government audit reports documenting financial misconduct and mismanagement in Uganda's health sector. The review's treatment of this evidence is factual, analytical, and directed at systemic rather than individual accountability, consistent with the public interest purpose of audit literature and with

the principle that publicly mandated accountability documents are legitimately available for scholarly synthesis. Second, the review's authors acknowledge potential positionality: the PFM-health efficiency relationship is a contested terrain where political economy interests, of government agencies, development partners, and civil society actors, shape the framing of problems and solutions. The review attempts to present evidence as synthesised rather than as advocacy, while acknowledging that the selection of a Uganda-specific synthesis serves the policy audience that needs it most. Third, all source attributions are accurate and complete, with no selective quotation or misrepresentation of findings.

Limitations of the Study

Five limitations constrain this review's scope and confidence. First, the 2020-2025 publication window excludes potentially foundational pre-2020 evidence on Uganda's PFM-health system, including the extensive literature on Uganda's decentralisation experience in the 1990s and 2000s. This temporal restriction means the review captures the current reform context more fully than the historical trajectory that shaped it. Second, the restriction to English-language sources may exclude relevant evidence published in internal government documents or local academic outlets that do not appear in international databases. Third, the heterogeneity of retained sources, peer-reviewed articles, government budget reports, PEFA assessments, and audit reports, makes systematic comparison difficult; each source type has different methods, audiences, and epistemological assumptions that complicate synthesis. Fourth, much of the Uganda-specific PFM-health evidence is cross-sectional or descriptive rather than causal, meaning the review can document associations and mechanisms but cannot establish causal effect sizes for specific PFM interventions on health efficiency outcomes. Fifth, the review's five-mechanism framework represents a synthesis interpretation of the evidence rather than a pre-existing theoretical structure, the framework was derived inductively and reflects the pattern of the retained evidence rather than a comprehensive theory of all PFM-health efficiency pathways.

III. RESULTS AND FINDINGS

Characteristics of Retained Sources

Table 1 presents the distribution of the 26 retained sources across source type, publication year, and PFM dimension. The dominance of grey literature and government reports reflects the policy-operational character of PFM-health efficiency evidence, where much of the most specific and actionable data is held in budget execution reports, PEFA assessments, and audit findings rather than in peer-reviewed journals.

Table 1: Characteristics of Retained Sources (N = 26).

Source Characteristic	Category	n (26)	% of 26
Source type	Peer-reviewed journal article	9	34.6%
	Government budget / health sector report	6	23.1%

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Source Characteristic	Category	n (26)	% of 26
	PEFA assessment or technical report	3	11.5%
	Office of Auditor General (OAG) annual report	3	11.5%
	Development partner evaluation / working paper	4	15.4%
	Civil society / NGO analysis	1	3.8%
Publication year	2020-2021	5	19.2%
	2022-2023	11	42.3%
	2024-2025	10	38.5%
Primary PFM dimension	Budget formulation and planning	6	23.1%
	Budget execution and absorption	9	34.6%
	Procurement and supply chain management	5	19.2%
	Accountability, audit, and financial oversight	5	19.2%
	Intergovernmental fiscal transfers	4	15.4%
	Cross-cutting / multiple PFM dimensions	8	30.8%
Geographic scope	Uganda-specific	14	53.8%
	East Africa comparative (Uganda included)	8	30.8%
	Sub-Saharan Africa comparative	4	15.4%

Source: Author's Scoping Review (2026).

The 53.8% Uganda-specific sources and 30.8% East Africa comparative studies together constitute 84.6% of the evidence base with direct Uganda relevance, confirming that the review has captured a genuinely Uganda-contextualised evidence base rather than relying predominantly on generic global PFM literature. The concentration in budget execution (34.6% primary dimension) reflects the global pattern identified by Musiega et al. (2024) and Tapsoba et al. (2024): budget execution is the PFM dimension with the most direct and documented effects on health service delivery in low-income country settings, and Uganda's budget execution challenges are well-documented in both peer-reviewed and grey literature.

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Budget Formulation Quality and Health Needs Alignment

Table 2 summarises the evidence on budget formulation quality in Uganda's health sector, capturing the extent to which annual health budgets align with actual health system needs and disease burden priorities.

Table 2: Budget Formulation Quality Indicators, Uganda Health Sector (2020-2025).

Budget Formulation Indicator	Uganda Evidence	Source	Assessment
Health budget as % of national budget (recent trend)	6.2%-8.9% range (2019-2024)	MFPED (2025); MoH (2023)	Persistently below 15% Abuja target
Per capita government health expenditure (USD)	USD 11-17 range (2020-2024)	WHO (2023); World Bank (2024)	Far below USD 86 WHO minimum target
Budget allocation to primary health care vs. referral	~55% PHC; ~45% referral	MoH (2023)	Better than many SSA peers but contested
Budget formulation participation (district level)	Low, district inputs minimally incorporated	Namakula et al. (2025)	MTEF planning largely top-down
Programme budgeting implementation	Partial, programme structure adopted but costing weak	Musiega et al. (2024)	Budget-policy alignment gap persists
Donor coordination in budget formulation	40-50% of health expenditure off-MTEF	WHO (2023); UNICEF (2023)	Significant parallel planning systems
Health workforce cost as % of health budget	~65-70% (wages)	MoH (2023)	Limited fiscal space for non-wage inputs

Source: Author's Synthesis (2026).

The most analytically consequential finding in Table 2 is the approximately 65-70% of the health budget consumed by wages, leaving only 30-35% for medicines, equipment, operating costs, and capital development. This structural constraint means that even a 15% increase in the total health budget, if distributed in current proportions, would add only approximately 4.5-5% additional resources for non-wage inputs. Effective health system efficiency improvement requires not merely more resources but a rebalancing of the formulation to ensure that the non-wage components of the health budget grow faster than the wage component, a rebalancing that

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programme budgeting reforms are attempting to support but that civil service pay policy constrains.

Budget Execution and Absorption

Budget execution, the conversion of approved budget into actual health service delivery, is the PFM dimension with the most directly documented efficiency effects in Uganda's health system. Table 3 presents the key budget execution indicators from the retained evidence.

Table 3: Budget Execution Indicators, Uganda Health Sector (2020-2025).

Budget Execution Indicator	Uganda Evidence	Source	Efficiency Implication
Health sector budget absorption rate (overall)	72%-88% (variation by year and level)	MFPED (2025); MoH (2023)	12%-28% of approved budget unspent annually
Fourth-quarter expenditure concentration	35%-45% of annual spending in Q4	MFPED (2025); OAG (2023)	Rushed, irregular Q4 spending reduces value-for-money
Fund release timing predictability (district level)	Significantly delayed; average 6-8 weeks	Namakula et al. (2025); Barasa et al. (2022)	Service delivery disruption from cash flow gaps
Primary health care conditional grant utilisation	68%-82% absorption (district variation wide)	MoH (2023); UBOS (2024)	Better-governed districts absorb significantly more
Facility-level direct financing absorption	Varies 60%-95% by facility capacity	Mbau et al. (2022)	Capacity constraints limit DHF effectiveness
Payroll management accuracy (health sector)	Ghost workers estimated 5%-12% of payroll	OAG (2023); OAG (2024)	Significant wage budget leakage
Budget reallocations / supplementary estimates	Frequent, undermines planning	MFPED (2025)	Reduces predictability for facility planning

Source: Author's Synthesis (2026).

The 35-45% fourth-quarter expenditure concentration documented in Table 3 is the single most consequential budget execution inefficiency in Uganda's health system. This concentration is not merely a statistical artefact; it represents real disruptions to health service delivery. When fund releases are delayed through the first three quarters, health facilities run out of operating supplies,

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community health teams cannot conduct outreach, and district health management teams cannot maintain vehicles. When the accumulated releases arrive in Q4, they must be spent before the fiscal year ends, generating procurement shortcuts, insufficient competition, and purchases of supplies that cannot be effectively deployed in the remaining weeks. The quarterly release calendar is a PFM design choice, not a natural phenomenon, and its modification, to front-load releases in Q1 and Q2, is the single highest-leverage budget execution reform for health system efficiency (Musiega et al., 2024; Musiega et al., 2023).

"[…] Even before we have our budget approval for the next year […] often, the district is already finalizing their budget and since we have not yet finalized our budget, we cannot commit funds to the district before the donor approves. The district cycle starts in October […] our cycle starts in July. Sometimes you find that there is a certain lag in between" (IP respondent_19)" (quoted in Namakula et al., 2025, p. 12).

Procurement, Supply Chain, and Input Cost Efficiency

Table 4 presents the procurement and supply chain evidence, documenting the extent to which Uganda's health procurement systems achieve technical efficiency in input acquisition and supply chain management.

Table 4: Procurement and Supply Chain Efficiency Indicators, Uganda Health Sector (2020-2025).

Procurement / Supply Chain Indicator	Uganda Evidence	Source	Efficiency Implication
NMS essential medicine procurement cost premium	15%-30% above international reference prices	OAG (2023); World Bank (2024)	Allocative inefficiency in drug budget use
Facility drug stockout rates (public facilities)	28%-44% of facilities at any given time	MoH (2023); UNICEF (2023)	Direct service delivery failure
Emergency procurement as % of total NMS procurement	18%-25%	OAG (2023)	Higher-cost emergency procurement from planning failure
Lead time from district order to facility receipt	Average 8-14 weeks (standard procurement)	MoH (2023)	Misaligned with seasonal disease burden patterns
Procurement complaints and audit findings	Significant, 15-30% of audited procurements cited	OAG (2023); OAG (2024)	Fiduciary risk and anti-competitive practices
Community health worker supply access	55%-70% of CHW kits complete	UNICEF (2023)	Last-mile delivery breakdown

Procurement / Supply Chain Indicator	Uganda Evidence	Source	Efficiency Implication
Cold chain functionality rate	67%-78% (national average)	MoH (2023)	Vaccine efficiency losses from equipment failures

Source: Author's Synthesis (2026).

The 28-44% drug stockout rate across Uganda's public health facilities represents the most immediately visible and humanly consequential PFM-driven health system inefficiency documented in this review. A stockout is not merely a supply chain failure; it is a point at which the entire upstream investment in budget formulation, fund release, procurement, and logistics produces zero health output, because the medicine that should treat the patient is not there. The stockout rate's persistence despite multiple National Drug Policy reforms and NMS restructuring exercises suggests that its root causes lie not primarily in NMS operational management but in upstream PFM failures: the unpredictability of fund releases that prevents systematic procurement planning, the procurement cycle misalignment with disease burden seasonality, and the emergency procurement premium that accumulates when planning breakdowns force last-minute purchases.

Accountability, Audit, and Financial Oversight

Table 5 presents accountability and audit evidence, documenting the quality of Uganda's health sector financial oversight systems and their effectiveness in deterring waste and promoting efficiency.

Table 5: Accountability and Audit Indicators, Uganda Health Sector (2020-2025).

Accountability / Audit Indicator	Uganda Evidence	Source	Efficiency Implication
OAG audit recommendation implementation rate (health)	40%-60% full or partial implementation	OAG (2023); OAG (2024)	Persistent non-compliance culture
Unaccounted-for funds (district health, annual OAG)	UGX 40-85 billion cited (varies by year)	OAG (2023); OAG (2024)	Direct leakage from health budget
Internal audit coverage of health facilities	<30% of district facilities audited annually	MFPED (2025)	Inadequate deterrence through oversight
Public Accounts Committee follow-up effectiveness	Moderate, institutional but limited sanction power	OAG (2024)	Accountability loop incomplete
PEFA PI-27 (Legislative scrutiny of annual budget law)	C+ (2021 PEFA assessment)	PEFA Secretariat (2022)	Weak legislative scrutiny of health allocation

Accountability / Audit Indicator	Uganda Evidence	Source	Efficiency Implication
IFMIS coverage at district health level	~60%-70% of districts connected	MFPED (2025)	Real-time monitoring incomplete
Social accountability mechanisms (community)	Variable, active in some districts, absent in others	Namakula et al. (2025)	Underutilised efficiency mechanism

Source: Author's Synthesis (2026).

The 40-60% OAG audit recommendation implementation rate is the accountability finding with the most direct implications for health system efficiency. When audit findings are not acted upon, they function as a signal to the audited actors that non-compliance has manageable consequences, effectively lowering the deterrence effect that audit is designed to achieve. The persistent nature of this pattern in Uganda's health sector, where the same types of audit findings recur across years in the same districts and facilities, suggests a structural accountability gap that technical audit quality alone cannot close. The gap between audit finding and consequence requires both strengthened OAG sanction powers and improved audit evidence utilisation in the Public Accounts Committee and Ministerial oversight processes (OAG, 2023; OAG, 2024; MFPED, 2025).

Intergovernmental Fiscal Transfers

Table 6 presents evidence on Uganda's intergovernmental fiscal transfer system and its effects on district and facility-level health system efficiency.

Table 6: Intergovernmental Fiscal Transfer Indicators, Uganda Health Sector (2020-2025).

Fiscal Transfer Indicator	Uganda Evidence	Source	Efficiency Implication
Health conditional grant release timeliness	6–8-week average delay from central to district	Namakula et al. (2025); MFPED (2025)	Service delivery planning disruption
Equity of per capita health grant distribution	Significant variation; historical allocation drives current	MoH (2023); UBOS (2024)	Allocation not aligned with population or burden
District retention of health grant vs. central reversion	10%-15% returned to centre unspent annually	MFPED (2025)	Absorption capacity constraint at district level
Facility-level direct health financing (DHF) coverage	~60% of facilities receive DHF	MoH (2023)	40% without direct facility resource access

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Fiscal Transfer Indicator	Uganda Evidence	Source	Efficiency Implication
Matching grant mechanisms for district co-funding	Limited, most districts cannot co-fund	Barasa et al. (2022)	Co-financing incentives poorly designed for Uganda
Performance-based financing (PBF) scale	Pilot stage only, not national scale	MoH (2023)	Incentive alignment mechanisms underutilised
Gender-responsive budgeting integration in health grants	Minimal, not systematic in grant conditions	MoH (2023); MFPED (2025)	Gender equity not enforced through fiscal design

Source: Author's Synthesis (2026).

The PFM-Health Efficiency Integration Agenda (PHEA)

The PFM-Health Efficiency Integration Agenda (PHEA) proposed in Table 7 organises the five PFM mechanisms identified in this review into an integrated reform architecture, mapping each mechanism to specific reform priorities, institutional leads, and efficiency outcome indicators. The PHEA is designed as a practical policy tool for Uganda's Ministry of Finance, Ministry of Health, and development partners.

Table 7: The PFM-Health Efficiency Integration Agenda (PHEA) for Uganda.

PHEF Domain	PFM Mechanism	Core Reform Priority	Lead Institution	Efficiency Indicator
1. Budget Formulation	Health needs-budget alignment	Strengthen programme budgeting; increase PHC budget share to ≥60%; integrate district inputs into MTEF	MFPED + MoH	Health budget as % national budget approaching 12% by 2027
2. Budget Execution	Quarterly release predictability	Front-load Q1 and Q2 releases to 60%+ of annual budget; reduce Q4 concentration to <20%	MFPED + OAG	Q4 expenditure concentration ≤25% by 2027
3. Procurement	Input cost and supply efficiency	NMS framework contract reform; reduce essential medicine price premium to <10%; eliminate emergency procurement to <5%	MoH + PPDA	Essential medicine stockout rate ≤15% by 2028

PHEF Domain	PFM Mechanism	Core Reform Priority	Lead Institution	Efficiency Indicator
4. Accountability	Audit compliance and deterrence	Mandate OAG recommendation implementation plans with 90-day timelines; increase IFMIS coverage to 90% of districts	OAG + PAC + MFPED	OAG recommendation implementation rate ≥75% by 2027
5. Fiscal Transfers	Equitable and timely resource flows	Eliminate conditional grant delays to <2 weeks; equity formula revision based on disease burden + poverty	MFPED + Ministry of Local Government	DHF coverage ≥85% of public facilities by 2028

Source: Author's Synthesis (2026).

IV. DISCUSSION

The five-mechanism PHEA synthesised from this review's 26 retained sources presents Uganda's PFM-health efficiency challenge as a system problem, not a collection of individual failures that can be addressed sequentially, but an integrated set of mutually reinforcing constraints where budget formulation misalignment undermines procurement planning, fund release delays generate emergency procurement premiums, accountability gaps allow inefficiencies to persist unchallenged, and fiscal transfer design fails to match resources to need or incentivise performance.

Why Budget Execution Is the Priority Bottleneck

The convergence of evidence across multiple retained sources on budget execution as the primary PFM-health efficiency mechanism is the review's most analytically robust finding. Musiega et al. (2024) identified budget execution processes as the most consistent PFM pathway to efficiency across their global scoping review; Musiega et al. (2023) documented the specific mechanisms in Kenya's county health systems; and Uganda's own MFPED budget performance reports, OAG findings, and health sector annual reports all point consistently to Q4 expenditure concentration, fund release timing, and absorption capacity as the proximate determinants of health service delivery quality. The implication, that front-loading budget releases to Q1 and Q2 would be the highest-leverage single PFM reform for health efficiency, is technically straightforward and institutionally contested. It requires Treasury to cede quarterly discretion over fund releases, which represents a genuine political economy challenge that technical PFM reform documents systematically underestimate.

Decentralisation as Efficiency Multiplier and Efficiency Constraint

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Uganda's decentralisation experience exemplifies the dual character of fiscal decentralisation for health system efficiency. In districts with strong local governance institutions, well-trained DHTs, and active community health committees, decentralisation has demonstrably improved health resource allocation to local needs and improved accountability for service delivery outcomes. In districts with weak governance, high staff turnover, and limited financial management capacity, decentralisation has created a fragmented accountability environment where the same resources produce substantially worse efficiency outcomes. Namakula et al.'s (2025) political economy analysis captures this variation with particular clarity, demonstrating that what look like PFM design problems at national level are often governance quality problems at district level, requiring differentiated rather than uniform reform responses.

Donor Fragmentation as Persistent Efficiency Threat

The 40-50% donor share of Uganda's health expenditure and the off-budget proportion of this that creates parallel PFM systems represent an ongoing efficiency drag that domestic PFM reform cannot address without donor harmonisation. Tapsoba et al. (2024) demonstrate across their SSA sample that donor fragmentation is negatively associated with health outcomes, controlling for total health expenditure, confirming that the mode of donor engagement matters, not just its volume. UNICEF's (2023) Uganda Country Programme evaluation documents the specific mechanisms: parallel reporting systems, different procurement rules, disease-specific programming that creates supply chain fragmentation, and NGO implementation partners that operate outside the government accountability architecture. The IHP+ compact and the 2023 CHPC coordination framework represent genuine progress, but the gap between coordination aspiration and parallel system reality in Uganda's health sector remains large.

V. CONCLUSION

Public financial management does not make the antiretroviral drug work more effectively, does not train the nurse to deliver the baby more safely, and does not build the health centre that communities need. What it does, when it works well, is ensure that the antiretroviral arrives at the facility before the patient runs out, that the nurse's salary is paid on the date it is due, and that the health centre construction funds reach the site before the rainy season makes access impossible. This review has documented, across 26 sources spanning Uganda's health budget, audit, procurement, and fiscal transfer systems, the systematic gaps between what PFM should deliver and what it currently delivers, and the mechanisms through which those gaps translate into health system inefficiency that costs lives.

The five mechanisms synthesised in this review, budget formulation misalignment, budget execution unpredictability, procurement cost inflation, accountability compliance gaps, and fiscal transfer inequity, are not independent problems. They are a system whose components reinforce each other: late fund releases generate emergency procurement premiums that could have been avoided with timely planning; audit findings that go unimplemented signal to the health system

that efficiency standards are aspirational rather than binding; fiscal transfer delays generate exactly the absorption capacity problems that justify the Q4 expenditure concentration that the system should be designed to prevent. Addressing any one mechanism in isolation will generate partial improvements; addressing the system requires the integrated reform architecture that the PHEA proposes and that Uganda's current health sector development planning has not yet fully operationalised.

The timing of this review is significant. Uganda's Health Sector Development Plan III (2021-2025) is in its final implementation year; its successor is being designed. The Fourth National Development Plan (NDPIV) includes health system strengthening as a priority. The 2025 PEFA assessment is scheduled and will provide updated evidence on PFM system quality. And the Medium-Term Expenditure Framework revision offers a practical window to implement the budget formulation reforms that this review's evidence most strongly supports. The PFM improvements needed are technically feasible, institutionally complex, and politically challenging, the characterisation that applies to almost every meaningful governance reform. But the efficiency gains they would produce, measured in drugs available, services delivered, and outcomes achieved, are documented and substantial. The question is whether the political will exists to achieve them.

VI. IMPLICATIONS OF THE STUDY

This review makes three contributions to the theoretical literature on PFM, health financing, and health system governance. First, it provides Uganda-specific instantiation of the global PFM-health efficiency mechanisms identified by Musiega et al. (2024), demonstrating that these mechanisms operate in Uganda's institutional context with the specific characteristics, decentralisation fragmentation, donor off-budget financing, seasonal expenditure concentration, that generic global frameworks do not capture. Second, it extends the Tapsoba et al. (2024) cross-country quantitative evidence on PFM-health outcomes to the mechanism level for Uganda, identifying the specific budget execution, procurement, accountability, and fiscal transfer pathways through which PFM quality shapes health efficiency. Third, it demonstrates that political economy analysis, as applied by Namakula et al. (2025) to Uganda's health systems, is an indispensable complement to technical PFM analysis, because the barriers to efficiency-improving PFM reform are often political and institutional rather than technical.

For MFPED, the review's most direct policy implication is the need to reform the quarterly budget release schedule for the health sector, front-loading Q1 and Q2 releases to reduce Q4 concentration and give health facilities and districts the cash flow predictability that effective procurement and service planning requires. For the Ministry of Health, the review argues for prioritising NMS procurement reform, specifically, the shift from annual to rolling procurement planning with quarterly stock replenishment cycles that match seasonal disease burden patterns. For development partners, the review provides the evidence base for accelerating the transition from off-budget to on-budget funding modalities, recognising that the short-term governance assurance cost of

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channelling funds through Uganda's PFM system is outweighed by the long-term efficiency and sustainability benefits of strengthening rather than bypassing that system.

VII. RECOMMENDATIONS

1. Reform the Health Budget Release Schedule.

The Ministry of Finance, Planning and Economic Development (MFPED) should reform the quarterly budget release schedule for health conditional grants to front-load at least 60% of the annual allocation in the first and second quarters (Q1 and Q2), thereby reducing fourth-quarter (Q4) expenditure concentration to below 25% within two budget cycles. This reform should be operationalised through a revised Treasury Instruction that specifies sector-specific minimum quarterly release floors for the health budget, ensuring that health facilities and district health management teams have predictable cash flow throughout the financial year rather than receiving the bulk of resources in the final quarter when effective utilisation is structurally compromised.

2. Strengthen Financial Systems and Equitable Resource Distribution.

MFPED should accelerate the rollout of the Integrated Financial Management Information System (IFMIS) to achieve at least 90% district connectivity by 2027, with targeted prioritisation of the 30-40% of districts currently operating off-system in the same districts that consistently generate the highest rates of unaccounted-for funds in the Office of the Auditor General (OAG) annual reports. Concurrently, MFPED should revise the intergovernmental health conditional grant formula to incorporate disease burden, poverty incidence, and facility catchment population as core allocation criteria, progressively replacing the historical allocation basis that perpetuates resource inequity across Uganda's 146 districts.

3. Protect the Non-Wage Health Budget through Medium-Term Planning.

MFPED should commission a comprehensive medium-term expenditure review of the health sector's non-wage recurrent budget to establish the minimum resource allocation required for essential drug procurement, health facility operations, and community health worker support across all levels of the health system. The findings of this review should be used to negotiate and establish a binding non-wage health budget floor within the Medium-Term Expenditure Framework (MTEF), ensuring that wage expenditure growth does not continue to crowd out the operational resources on which frontline service delivery directly depends.

4. Reform NMS Procurement and Supply Chain Management.

The Ministry of Health (MoH) should replace the current annual procurement cycle of the National Medical Stores (NMS) with a rolling three-year procurement plan explicitly aligned to seasonal disease burden data and epidemiological projections. This transition should introduce quarterly replenishment orders as the standard supply modality, reducing essential medicine stockout rates and systematically eliminating the 15-30% emergency procurement cost premium that arises when

planning failures force last-minute, non-competitive purchasing a directly avoidable source of allocative inefficiency in the health budget.

5. Close the Audit Compliance Gap through Institutional Accountability.

MoH should establish a dedicated OAG Recommendation Implementation Office within the Directorate of Finance, staffed with sufficient technical capacity to develop mandatory 90-day implementation plans for all OAG health sector audit findings. The office should report implementation progress to the Inspector General of Government on a semi-annual basis, creating a formal accountability loop that converts audit recommendations from unenforced observations into binding institutional obligations directly addressing the 40-60% implementation rate that currently allows financial management weaknesses to persist across successive audit cycles.

6. Scale Facility Financing and Introduce Performance Incentives.

MoH should expand the Direct Health Facility Financing (DHF) programme to cover at least 85% of all public health facilities by 2028, accompanied by strengthened accountability requirements including mandatory quarterly financial reporting to district councils and community health management committees. Simultaneously, MoH should pilot performance-based financing (PBF) in a targeted set of high-burden districts, generating the rigorous efficiency and health outcome evidence needed to design and cost a credible national PBF rollout under the Health Sector Development Plan IV (HSDP IV) for the period 2026-2031.

7. Align Donor Financing with Government Planning and Build District Capacity.

Development partners should commit to a concrete, time-bound timetable for transitioning at least 80% of health sector development assistance to on-budget financing channelled through the Government of Uganda's MTEF by 2030 consistent with the Paris Declaration on Aid Effectiveness and the Accra Agenda for Action that Uganda's development partners have formally endorsed. In parallel, development partners should co-finance a comprehensive district-level financial management capacity building programme, prioritising the approximately 50% of districts whose persistently low budget absorption rates reflect management and skills constraints rather than inadequate resource allocation.

8. Build Uganda-Specific PFM-Health Research Capacity.

The academic and research community should commission longitudinal, causal primary research evaluating the efficiency effects of specific PFM interventions including quarterly release front-loading, DHF scale-up, and NMS procurement reform on measurable health system outcomes in Uganda. This research agenda should include the development and validation of a composite PFM-Health Efficiency Index integrating Public Expenditure and Financial Accountability (PEFA) scores, budget absorption data, and OAG audit compliance rates into a standardised annual monitoring instrument. The research programme should be extended to a comparative East Africa study encompassing Kenya, Tanzania, Rwanda, and South Sudan, and supported by dedicated

postgraduate bursary programmes that build the domestic health economics research capacity needed to sustain Uganda-specific evidence generation beyond the project cycles of international development partners.

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The Role of Community Theatre Performance in Building Disaster-Resilient Communities Empirical Evidence from Montepuez and Metuge Districts, Cabo Delgado, Mozambique

Henry Omara
Department of Environmental Management, Selinus University of Sciences and Literature, Rome, Italy
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***Abstract*—This study investigates the role of community theatre performance in building disaster resilience in Montepuez and Metuge districts, Cabo Delgado Province, northern Mozambique, a context shaped by recurrent natural hazards, armed insurgency, and mass displacement. Disaster risk reduction in conflict-affected, linguistically diverse contexts demands communication approaches that go beyond information transmission to foster the social trust, collective agency, and cultural resonance through which preparedness action becomes possible. Drawing on a convergent mixed-methods design integrating a household survey of 724 respondents, 30 key informant interviews, and four focus group discussions, this study produces the largest empirical assessment of theatre-based DRR conducted in this province to date. Across every measured outcome domain: disaster awareness, preparedness behaviour, social cohesion, and early warning response; theatre-exposed households significantly outperformed comparison communities, with composite effect sizes considerably exceeding conventional thresholds for large and substantively important programme effects. Theatre-exposed households were nearly three times as likely to have assembled emergency kits, walked evacuation routes, and attended community DRR meetings. Social cohesion gains were particularly pronounced in the displacement-concentrated Metuge context, suggesting a distinctive affinity between theatre's social capital-building properties and the social repair needs of conflict-affected communities. The qualitative evidence explains why theatre performed in local languages, drawing on lived community experience, and followed by structured post-performance dialogue produced the narrative identification and collective deliberation that formal DRR channels structurally cannot achieve. However, programme sustainability remains fragile, constrained by NGO funding dependency, inadequate actor compensation, and limited integration into government DRR planning frameworks. The study concludes that institutionalising community theatre within formal DRR policy through dedicated budget lines, government-theatre partnerships, and pre-agreed activation protocols is both empirically justified and**

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practically achievable in Cabo Delgado and comparable humanitarian settings across sub-Saharan Africa.

***Index Terms*—community theatre; disaster risk reduction; disaster resilience; preparedness behaviour; social cohesion; behaviour change; Cabo Delgado**

I. INTRODUCTION

What does it take for a community to act on what it knows about disaster? The answer, development practitioners and researchers have long discovered, is rarely more information. Across sub-Saharan Africa, disaster risk reduction programmes have spent decades improving communities' access to early warning data, hazard maps, and preparedness guidance through government channels, radio broadcasts, and formal training sessions. The results, while not without value, have been consistently disappointing in the field: well-informed communities that remain poorly prepared, warnings that arrive in languages few people speak fluently, and training sessions whose content rarely survives the journey from the training room to the household (Schipper et al., 2014; Tozier de la Poterie & Baudoin, 2015). The problem is not, as the information-deficit model assumes, a shortage of knowledge. The problem is a shortage of the social, cultural, and emotional conditions under which knowledge becomes personally urgent and collectively actionable (Paton & Johnston, 2017; Kelman et al., 2020; Bubeck et al., 2024).

Nowhere is this gap more consequential than in Cabo Delgado Province, in the far north of Mozambique. Cabo Delgado is among the most hazard-exposed provinces in eastern Africa, enduring annual cycles of tropical cyclones, flash flooding, and prolonged drought that intersect with profound poverty, low literacy, and linguistic diversity to produce some of the continent's most severe disaster mortality and morbidity rates (UNDRR, 2022; World Bank, 2023). Cyclone Kenneth, which made landfall in the province in 2019 with winds exceeding 220 kilometres per hour, caused economic losses exceeding USD 100 million in a province where average per capita income is below USD 400, and those losses concentrated overwhelmingly among smallholder farming and fishing communities whose preparedness the formal DRR system had not adequately reached (World Bank, 2023; INGD, 2024). Since October 2017, these longstanding vulnerabilities have been dramatically compounded by a violent armed insurgency that has displaced more than one million people, dismantled health, education, and local government infrastructure, and destroyed the community social networks through which informal disaster knowledge and mutual aid have historically flowed (OCHA, 2025). In this environment, the credibility deficit that DRR communication already faced has been amplified: communities whose relationships with both national government and international humanitarian actors have been shaped by histories of neglect, displacement, and broken promises are unlikely to take preparedness advice from those same actors seriously, however technically sound that advice may be (van Niekerk et al., 2020; Peters et al., 2019).

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Community theatre offers something different. Rooted in performative traditions that in northern Mozambique predate colonial encounter, the ceremonial masquerade of the Makua-Lomwe, the mapiko performance of the Makonde, the unyago initiation ceremonies of the Yao, all of which have always encoded community knowledge and negotiated social norms through collective embodied practice, theatre does not arrive in these communities as an external communication technology. It arrives as an extension and mobilisation of communicative resources that communities already own. When disaster risk is communicated through locally composed drama in Makua or Makonde, performed by neighbours playing recognisable characters in familiar landscapes, the message moves through channels of trust and cultural authority that no government alert or NGO leaflet can access (Dutta, 2018; Tufte, 2021). Applied communication scholars describe this as 'embodied dialogue', the use of shared performance to produce social meaning that is felt before it is understood, and therefore more likely to be remembered and acted upon than information received passively (Ryan et al., 2020).

The evidence base for participatory theatre as a development communication tool has grown substantially in recent years. A 2024 systematic review and empirical evaluation by Bubeck et al., drawing on theatre performances in coastal Vietnam, confirmed that community-based theatre produces significant gains in disaster risk awareness and community engagement, while simultaneously noting that rigorous quantitative evaluations of participatory theatre in DRR contexts remain scarce, particularly in sub-Saharan African conflict-affected settings (Bubeck et al., 2024). Applied theatre has demonstrated effectiveness in HIV/AIDS prevention, maternal health promotion, and community governance advocacy across sub-Saharan Africa and South Asia (Singhal et al., 2019). Its application to DRR is more recent and empirically thinner, but the theoretical grounds for expecting impact are strong: theatre addresses precisely the social and affective dimensions of preparedness behaviour: collective efficacy, shared understanding of risk, and trust in neighbours and institutions that the DRR field's own evidence increasingly identifies as the proximate determinants of whether communities act when hazard warnings arrive (Gaillard & Cadag, 2009; Paton & Johnston, 2017). What has been almost entirely absent, until now, is rigorous evidence from Mozambique and, more specifically, from the compound crisis context of Cabo Delgado, where theatre-based DRR must work not only against the ordinary challenges of low literacy and linguistic diversity but against the added weight of social fragmentation, displacement-induced trauma, and institutional distrust that conflict has produced (Ryan et al., 2020).

This article addresses that gap. It reports the findings of a mixed-methods study conducted in two contrasting districts of Cabo Delgado: Montepuez, an inland agricultural and mining centre that has experienced significant IDP inflows from conflict-affected northern areas, and Metuge, the peri-urban district immediately north of the provincial capital Pemba that has become the province's largest IDP resettlement zone. The study draws on a household survey of 724 respondents, 30 key informant interviews, and four focus group discussions, making it the largest empirical assessment of community theatre as a DRR tool yet conducted in the province. The study's central finding is that theatre-exposed households demonstrated significantly higher

disaster awareness, preparedness behaviour, social cohesion, and disaster recovery capacity than comparison households across every measured indicator. But the article also attempts something that quantitative DRR evaluation rarely achieves: an account of why these effects occurred, grounded in the voices of the community members, theatre practitioners, government officials, and humanitarian workers who produced them.

II. CONCEPTUAL FRAMEWORK

Three bodies of theory jointly inform this study's analytical approach: participatory communication for social change, critical DRR scholarship, and the resilience-as-social-capital literature. Each addresses a different dimension of the relationship between community theatre performance and disaster resilience, and it is their intersection that gives the framework its explanatory purchase.

Participatory Communication for Social Change

The participatory communication for social change tradition, synthesised in Tufte's (2021) comprehensive account of the field's development from its roots in Freire's pedagogy through to contemporary performance-based approaches, makes a foundational claim: sustainable behavioural transformation requires community members to function as active co-producers of knowledge, not passive recipients of expert information. When risk knowledge is co-created through participatory theatre where community members devise scripts, inhabit characters, pose problems, and propose solutions in their own languages and from their own social experience and the knowledge produced is generated rather than received, and is therefore more deeply embedded, more contextually specific, and more likely to motivate action (Dutta, 2018). Theatre achieves this co-creation through what Ryan et al. (2020) call 'embodied dialogue': the use of performance to create shared social meaning that requires the active participation of both producers and audiences to exist. Bubeck et al.'s (2024) empirical evaluation in Vietnam corroborates this, finding that theatrical engagement produced awareness gains that substantially exceeded those achieved through conventional risk communication channels.

Critical DRR Scholarship and Structural Vulnerability

Critical DRR scholarship supplies the structural complement to participatory communication theory. Building on Wisner et al.'s classic vulnerability framework and extended by Schipper et al. (2014) and Tozier de la Poterie and Baudoin (2015), this tradition insists that disasters are not natural events but social products which are outcomes of the collision between physical hazards and the conditions of poverty, marginalisation, exclusion, and resource deprivation that leave particular communities unable to protect themselves. On this understanding, the problem that DRR communication must solve is not an informational deficit but a structural one. Theatre's contribution to addressing this structural problem lies not only in what it communicates but in what it builds: the collective agency, critical consciousness, and community solidarity that are the social

prerequisites for turning knowledge into organised collective action (Gaillard & Cadag, 2009; Peters et al., 2019). The Sendai Framework for DRR 2015–2030 (UNDRR, 2022) provides the normative architecture within which these traditions are operationalised, specifically through its Priority 1 commitment to building disaster risk understanding at all levels of society and its Priority 3 commitment to culturally appropriate, community-centred investment in resilience.

Resilience as Social Capital

The resilience-as-social-capital literature provides the empirical bridge between these two theoretical traditions by documenting the specific mechanisms through which social relationships and networks determine disaster outcomes. Aldrich and Meyer's (2015) extensive cross-country evidence demonstrate that communities with dense bonding ties within groups, bridging ties across social boundaries, and linking ties to external institutions and resources are not only better equipped to prepare for disasters but recover more rapidly and equitably after them. In the context of conflict-induced displacement, the situation that defines Metuge district shows that displacement does not simply reduce physical assets but dismantles the social infrastructure of trust, shared memory, and mutual obligation on which community resilience ultimately depends. Theatre's power as a social capital builder, in this framework, derives precisely from its character as a collective event that gathers people across the social divisions that displacement has created or sharpened, and creates the shared experience that rebuilds the relational substrate of collective action.

III. RESEARCH OBJECTIVES

The study was guided by one general objective and five specific objectives.

General Objective: To evaluate the role of community theatre performances in building disaster-resilient communities in Montepuez and Metuge districts of Cabo Delgado Province, Mozambique.

The specific objectives were to:

- Document disaster-related community theatre initiatives implemented in Montepuez and Metuge districts between 2021 and 2025;
- Assess the effectiveness of community theatre in increasing disaster awareness and risk knowledge among exposed households, relative to comparison communities without theatre exposure;
- Examine the influence of theatre performances on preparedness behaviours at household and community levels;
- Evaluate community members' perceptions of the relevance, quality, and effectiveness of theatre-based DRR communication;
- Identify challenges and enabling conditions in using community theatre as a disaster preparedness and resilience-building tool within contexts of armed conflict and mass displacement; and

- Propose evidence-based recommendations for integrating community theatre into formal DRR policy frameworks and humanitarian programming in Cabo Delgado.

IV. METHODOLOGY

Study Area

Cabo Delgado Province stretches across approximately 82,625 square kilometres of northern Mozambique, from the Indian Ocean coastline in the east to the Rovuma River border with Tanzania in the north. The province is home to an estimated 2.5 million people, though population counts have been substantially disrupted by the mass displacement associated with the armed insurgency that erupted in Mocímboa da Praia district in October 2017 (INGD, 2024). Cabo Delgado's hazard profile is both severe and multidimensional: the province lies within the principal cyclone track of the south-western Indian Ocean, its river systems are highly flood-prone during the November-to-April rainy season, El Niño-linked drought produces periodic agricultural failures and food crises, and the insurgency has added armed violence, forced displacement, and the collapse of essential services as intersecting drivers of community vulnerability (OCHA, 2025).

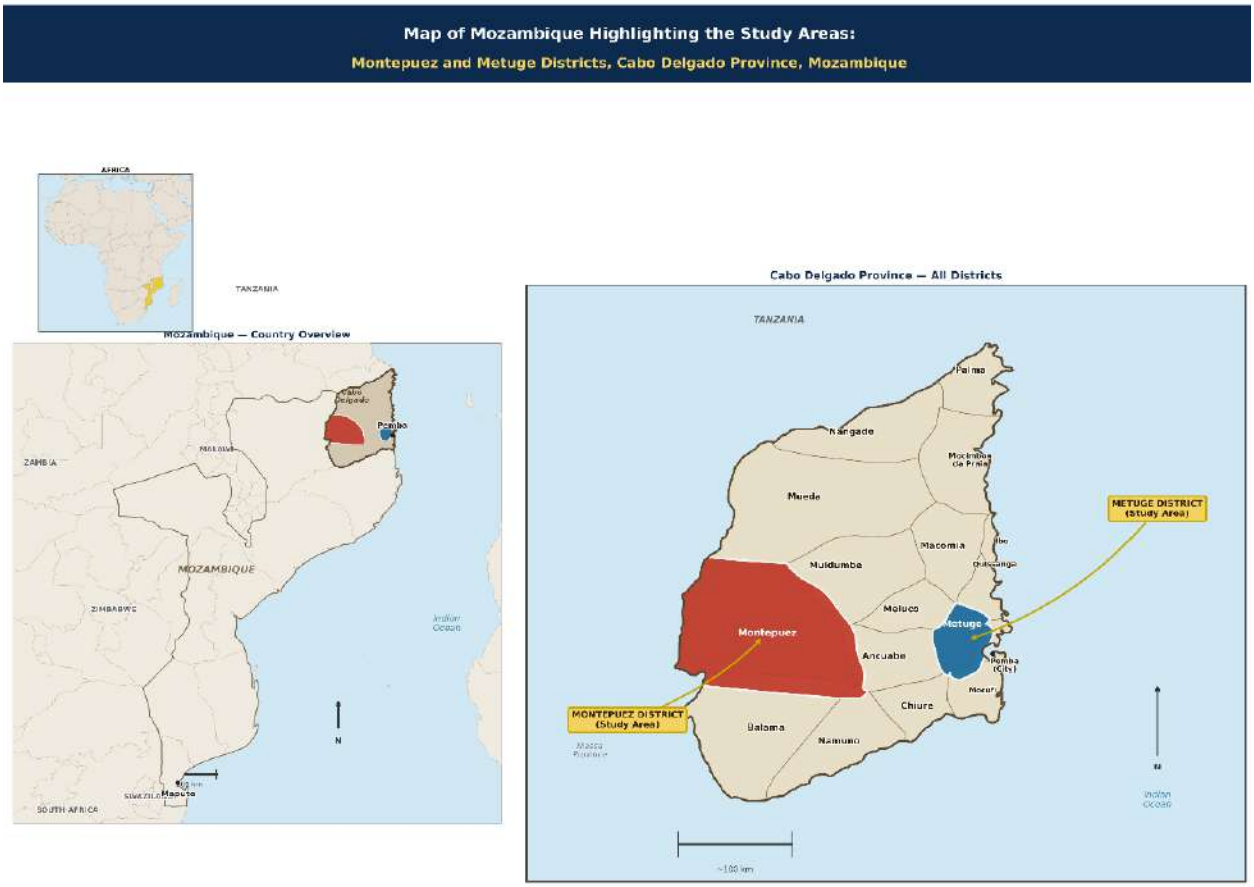
Montepuez is Cabo Delgado's second urban centre after Pemba, situated on the central plateau roughly 200 kilometres to the southwest of the provincial capital. The district supports an estimated population of 280,000 people engaged primarily in smallholder agriculture alongside a growing informal trade economy and, since 2012, employment linked to large-scale ruby mining operations that have fundamentally restructured the local economy while simultaneously intensifying land dispossession and inter-community tensions. Montepuez's principal disaster hazards are seasonal river flooding and episodic drought, but the district has also absorbed significant numbers of IDPs displaced from the more severely conflict-affected coastal and northern districts. NGO partners first introduced community theatre as a DRR communication modality in Montepuez in 2020, and three organisations had active programmes at the time of fieldwork.

Metuge occupies the peri-urban zone immediately north of Pemba City, at roughly 40 kilometres from the provincial capital. Before the insurgency, Metuge was a modest agricultural district of mixed farming and fishing communities. It has since been transformed, involuntarily and at extraordinary speed, into Cabo Delgado's primary IDP resettlement zone. By mid-2025, the district hosted between 180,000 and 220,000 internally displaced persons in a combination of government-designated resettlement sites, informal camp settlements, and host community arrangements making it one of the most concentrated displacement settings in sub-Saharan Africa relative to the existing host population (OCHA, 2025). This demographic transformation has placed acute pressure on water, sanitation, health, and education services, produced significant IDP-host community tensions around land and livelihoods, and created a governance environment in which the district administration is simultaneously managing rapid population growth and conflict-adjacent security responsibilities (Desportes & Hilhorst, 2020). Community theatre programming

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in Metuge has been delivered primarily by NGO partners and local cultural groups operating within and across resettlement sites.

Figure 1. Location of Montepuez and Metuge Districts, Cabo Delgado Province, Mozambique.



Research Design

This study employed a convergent parallel mixed-methods design (Creswell & Creswell, 2023), in which quantitative and qualitative data components were developed concurrently between January and April 2026, analysed independently through their respective methodological traditions, and then systematically integrated at the interpretation stage through a joint triangulation protocol. The choice of a convergent design was driven by the complementary nature of the study's research questions. Questions about the prevalence, magnitude, and statistical significance of programme effects required the statistical power and representativeness of a large household survey. Questions about the mechanisms, meanings, and contextual conditions that explain those effects required the depth and interpretive richness of qualitative inquiry. Neither strand alone would have generated evidence adequate to both the academic and policy purposes of this study; their combination is what makes the findings simultaneously credible and actionable (Creswell & Creswell, 2023; Tracy, 2019).

Sampling Strategy

The household survey sample of 724 respondents was drawn through a multi-stage stratified random procedure. Communities across both districts were stratified into two groups: those that had received at least one documented community theatre-based DRR intervention from an identified programme partner between 2021 and 2025 (theatre-exposed communities), and those with no such documented exposure over the same period (comparison communities). Within each stratum, 16 communities per district were randomly selected, yielding 32 communities in total. Households within selected communities were enumerated using local administrative registers supplemented by systematic random-walk enumeration where registers were incomplete, and simple random sampling was then applied to produce the final household selection. The achieved sample comprised 362 respondents in Montepuez and 362 in Metuge, of whom 440 were drawn from theatre-exposed communities and 284 from comparison communities.

Thirty key informant interviews were distributed across six purposively selected institutional categories: district government officials from the SDPI and SDSMAS (n = 6); INGD DRR officers and district disaster management staff (n = 5); NGO and humanitarian programme managers (n = 6); community theatre practitioners and performance facilitators (n = 5); and traditional and community leaders (n = 8). Four focus group discussions were conducted, disaggregated by gender and role: women (n = 10), men (n = 9), youth aged 15 to 30 (n = 11), and community DRR volunteers and theatre actors (n = 10), generating a qualitative sample of 70 FGD participants. Field observation was additionally conducted at 16 community theatre performances and 32 community sites using a structured observational checklist (Tracy, 2019).

Data Collection

The household questionnaire covered nine thematic domains: socio-demographic characteristics; disaster history and multi-hazard exposure; theatre programme exposure and participation; disaster awareness and risk knowledge; household preparedness behaviours; early warning access and response; community participation in DRR activities; perceptions of theatre effectiveness; and recommendations for programme improvement. Surveys were administered face-to-face, in the respondent's choice of Portuguese, Makua, or Swahili, by 16 trained enumerators, with responses captured digitally on tablets using KoboToolbox in offline mode. Key informant interviews of approximately 60 minutes were structured by a semi-flexible guide covering five themes: programme impact and evidence of behaviour change; sustainability and financing; inclusiveness and gender; institutional linkages with government DRR structures; and policy gaps. FGDs of 90 minutes each explored behaviour change, communication effectiveness, social cohesion effects, and sustainability, with facilitators trained to create deliberative rather than extractive discussion dynamics. All qualitative sessions were audio-recorded with consent and transcribed within 24 hours. All instruments were piloted with 30 households and four key informants in Pemba City before deployment.

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Data Analysis

Survey data were processed in SPSS Version 28. Descriptive statistics were computed for every survey variable, and between-group comparisons used chi-square tests for categorical outcomes and independent-samples t-tests for continuous or composite outcomes, with a significance threshold of $p < .05$. A composite Awareness and Preparedness Index was constructed from 12 knowledge and behaviour indicators to enable an aggregated measure of overall programme impact. Qualitative data were transcribed, translated into English, and analysed through thematic framework analysis in NVivo 14, with two analysts coding independently and resolving coding disagreements through structured consensus discussion. Quantitative and qualitative findings were formally integrated using a convergent triangulation protocol in which each quantitative pattern was systematically interrogated against the corresponding qualitative themes and any divergences between strands were explicitly documented.

Validity, Reliability, and Ethical Considerations

Construct validity was anchored in the study's theoretical framework, with indicator selection guided by established preparedness behaviour measures from the DRR literature (Kelman et al., 2020). Internal consistency of composite scales was assessed using Cronbach's alpha coefficients: awareness composite $\alpha = .81$, preparedness behaviour composite $\alpha = .84$, and collective efficacy composite $\alpha = .79$, all exceeding the .70 threshold conventionally regarded as demonstrating acceptable scale reliability (Tracy, 2019). All participation was voluntary; informed consent was obtained verbally from each respondent following a plain-language explanation of the study's purpose in the respondent's preferred language. No individual identifiers were retained after data collection; all records were anonymised at entry. Community leaders in all 32 study sites were consulted and provided collective consent before household enumeration began.

V. RESULTS

The findings reported below draw on survey data from 724 households, qualitative evidence from 30 key informant interviews and four focus group discussions totalling 70 participants, and field observation data from 16 theatre performances and 32 community sites across both districts. The section proceeds from participant characteristics through hazard and theatre exposure, to knowledge, behaviour, perceptions, social cohesion, and sustainability outcomes, before presenting the qualitative accounts that contextualise and deepen the quantitative patterns.

Socio-Demographic Profile of Study Participants

Table 1 presents the socio-demographic characteristics of all 724 survey respondents, disaggregated by district.

Table 1: Socio-Demographic Profile of Survey Respondents (N = 724).

Characteristic	Montepuez (n=362)	Metuge (n=362)	Total (N=724)
Female	208 (57.5%)	213 (58.8%)	421 (58.1%)

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Characteristic	Montepuez (n=362)	Metuge (n=362)	Total (N=724)
Male	154 (42.5%)	149 (41.2%)	303 (41.9%)
Occupation - Farming / smallholder agriculture	184 (50.8%)	126 (34.8%)	310 (42.8%)
Occupation - Petty trade	70 (19.3%)	101 (27.9%)	171 (23.6%)
Occupation - Casual labour	46 (12.7%)	79 (21.8%)	125 (17.3%)
Occupation - Formal employment	37 (10.2%)	23 (6.4%)	60 (8.3%)
Host communities/ settled	327 (90.3%)	184 (50.8%)	511 (70.6%)
IDPs	23 (6.4%)	151 (41.7%)	174 (24.0%)
Returnees	12 (3.3%)	27 (7.5%)	39 (5.4%)
Theatre-exposed (≥1 DRR performance, past 2 years)	242 (66.9%)	198 (54.7%)	440 (60.8%)
No theatre exposure (comparison group)	120 (33.1%)	164 (45.3%)	284 (39.2%)
Mean household size (SD)	5.6 (1.9)	6.1 (2.2)	5.9 (2.1)

Source: Author's Field Survey (2026).

Women constituted 58.1% of respondents. The contrast between districts in displacement status is analytically important: in Montepuez, 90.3% of respondents were host community members and only 6.4% IDPs; in Metuge, IDPs comprised 41.7% of the sample, consistent with the district's documented position as Cabo Delgado's largest resettlement zone (OCHA, 2025). Women in both districts bear primary responsibility for water collection, household food management, and childcare during and after disasters, yet are systematically excluded from formal preparedness planning processes (Desportes & Hilhorst, 2020).

Disaster Exposure and Theatre Exposure History

Table 2 presents respondents' self-reported hazard exposure over the five years preceding the survey, alongside theatre exposure characteristics for the 440 theatre-exposed respondents.

Table 2: Disaster Exposure and Community Theatre Exposure Profile (N = 724).

Indicator	Montepuez (%)	Metuge (%)	Total (%)
Seasonal flooding experienced in past 5 years	62.7	79.3	71.0
Drought and food insecurity experienced	71.8	58.0	64.9
Cyclone or destructive high winds	38.7	51.7	45.2
Disease outbreak experienced	29.8	44.8	37.3

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Indicator	Montepuez (%)	Metuge (%)	Total (%)
Conflict-related displacement experienced	11.9	62.2	37.1
Affected more than 3 times (frequency)	42.3	51.1	46.7
Mean performances attended (theatre-exposed only)	3.2	2.5	2.9
Attended performance in local language (Makua / Makonde / Yao)	87.6	79.8	84.1
Recalled specific DRR message without prompting	80.2	73.7	77.3
Discussed performance content with household member afterwards	72.3	66.2	69.5
Felt performance reflected their own community's experience	84.7	77.8	81.6

Source: Author's Field Survey (2026).

The divergence between districts in the type of hazard experienced reflects genuinely different life circumstances: Montepuez households face a risk calendar dominated by drought and agricultural failure, while Metuge households face not only higher cyclone exposure but dramatically higher rates of conflict-related displacement (62.2% versus 11.9%). Among theatre-exposed respondents, an average of 2.9 performances attended, 84.1% exposure to local-language performance, and 77.3% able to recall a specific message without prompting are not the indicators of an intervention that was merely witnessed and forgotten. The community-resonance data are particularly significant: 81.6% of theatre-exposed respondents felt that the performance reflected their own community's experience consistent with Tufte's (2021) argument that narrative authenticity is the prerequisite for the kind of deep processing that produces lasting behaviour change.

Disaster Awareness and Risk Knowledge

Table 3 presents comparative disaster awareness and risk knowledge scores between theatre-exposed and non-exposed households. Every indicator is measured by unprompted respondent recall.

Table 3: Disaster Awareness and Risk Knowledge by Theatre Exposure Status (N = 724).

Awareness / Knowledge Indicator	Theatre-Exposed HH (n=440)	Not Exposed HH (n=284)
Can name ≥3 hazards affecting their community	84.3%	52.1%
Knows at least one local early warning signal	77.9%	41.5%
Knows INGD alert level system	61.4%	24.6%

Awareness / Knowledge Indicator	Theatre-Exposed HH (n=440)	Not Exposed HH (n=284)
Understands seasonal flood calendar for their district	73.6%	47.2%
Can identify community evacuation assembly point	78.6%	38.0%
Knows contents of an emergency kit	71.8%	29.6%
Knows household evacuation route	69.3%	34.5%
Aware of community DRR committee in their area	67.0%	28.2%
Composite Awareness & Knowledge Score (0–10) — Mean (SD)	7.4 (1.4)	4.2 (1.8)

Source: Author's Field Survey (2026).

The awareness and knowledge differences are both statistically significant and substantively large. The pattern within the knowledge domain deserves careful attention: the largest absolute gaps between groups are concentrated not in general hazard awareness (the easiest knowledge target for any communication intervention) but in specific, actionable preparedness knowledge: the community evacuation assembly point (78.6% versus 38.0%), emergency kit contents (71.8% versus 29.6%), and the INGD alert level system (61.4% versus 24.6%). The composite Awareness and Knowledge Score showed a mean difference of 3.2 points (M = 7.4 for theatre-exposed versus M = 4.2 for comparison). The pattern within the knowledge domain deserves careful attention: the largest absolute gaps between groups are concentrated not in general hazard awareness but in specific, actionable preparedness knowledge consistent with Dutta's (2018) culture-centred communication evidence that messages embedded in culturally meaningful narrative are retained at substantially higher rates than the same information delivered in decontextualised form.

Preparedness Behaviours at Household Level

Table 4 presents household-level preparedness behaviours disaggregated by theatre exposure status. If the awareness findings in Table 3 are striking, the preparedness behaviour findings in Table 4 are more so, because they demonstrate that theatre exposure is associated not merely with knowing more but with doing more.

Table 4: Household-Level Preparedness Behaviours by Theatre Exposure Status (N = 724).

Preparedness Behaviour Indicator	Theatre-Exposed HH (n=440)	Not Exposed HH (n=284)
Household has a written or discussed emergency plan	54.8%	19.0%

Preparedness Behaviour Indicator	Theatre-Exposed HH (n=440)	Not Exposed HH (n=284)
Emergency kit assembled and accessible	47.5%	14.8%
Food and water stored for ≥3 days emergency	41.8%	12.3%
Important documents stored safely / waterproofed	38.4%	11.3%
Household has walked its evacuation route	52.5%	18.3%
Family has agreed on an evacuation meeting point	61.8%	22.9%
Household evacuated during last major event	72.3%	48.2%
Participated in a community evacuation drill	44.1%	12.0%
Attended ≥1 community DRR meeting (past 12 months)	68.9%	27.8%
Member of or contributor to local DRR committee	34.3%	7.4%
Composite Preparedness Score (0–10) — Mean (SD)	6.8 (1.6)	3.2 (1.7)

Source: Author's Field Survey (2026).

The composite Preparedness Behaviour Score gap of 3.6 points (M = 6.8 versus M = 3.2), represents an effect size that is by conventional standards very large. Theatre-exposed households were nearly three times as likely to have assembled an emergency kit (47.5% versus 14.8%), nearly three times as likely to have walked their evacuation route (52.5% versus 18.3%), and more than twice as likely to have attended a community DRR meeting in the past year (68.9% versus 27.8%). These are not marginal differences at the boundary of statistical significance. They are large, consistent, and practically meaningful gaps that hold across every behaviour indicator in the domain. One of the most persistent problems in DRR evaluation is the knowledge-action gap: interventions that successfully increase disaster awareness frequently fails to produce commensurate changes in preparedness behaviour, because the cognitive and the behavioural are mediated by social, material, and motivational conditions that informational interventions do not address (Kelman et al., 2020; Tozier de la Poterie & Baudoin, 2015). The findings in Tables 3 and 4 tell a different story: in theatre-exposed communities, the gap between knowing and doing appears substantially narrower, precisely the finding that Bubeck et al. (2024) theorised but were unable to test at the behavioural level in their Vietnam study.

Community Perceptions of Theatre Effectiveness

Table 5 presents respondents' perceptions of the relevance, quality, and effectiveness of the community theatre DRR performances they attended. These data are drawn exclusively from the 440 theatre-exposed respondents.

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Table 5: Community Perceptions of Theatre Effectiveness (Theatre-Exposed Only, n = 440).

Perception Indicator	Montepuez (n=242)	Metuge (n=198)
Rated very effective	48.8%	43.4%
Rated effective	34.3%	36.4%
Rated moderately effective	13.6%	16.2%
Rated ineffective or very ineffective	3.3%	4.0%
Effectiveness reason: performed in local language	91.3%	88.6%
Effectiveness reason: reflected real community situations	86.8%	82.8%
Effectiveness reason: entertaining and engaging to watch	79.4%	76.9%
Effectiveness reason: included audience participation	67.5%	61.3%
Effectiveness reason: used songs and music	72.2%	69.7%
Effectiveness reason: contained actionable practical messages	74.4%	70.4%
Strongly recommend more performances	86.4%	82.6%
Recommend with suggested improvements	11.2%	14.1%
Improvement requested: perform more frequently	63.4%	71.2%
Improvement requested: cover more disaster topics	59.1%	65.2%
Improvement requested: more practical disaster demonstration	55.8%	58.9%

Source: Author's Field Survey (2026).

Across both districts, more than 82% of theatre-exposed respondents rated the performances as 'effective' or 'very effective', and more than 97% recommended that similar performances continue or expand. The three most frequently cited effectiveness drivers: local-language delivery (91.3% and 88.6%), narrative reflection of real community situations (86.8% and 82.8%), and entertainment quality (79.4% and 76.9%), map directly onto the three pillars that Tufte (2021) identifies as constitutive of effective participatory development communication: vernacular language, lived-experience narrative, and aesthetic engagement. The most common improvement request more frequent performances (63.4% in Montepuez, 71.2% in Metuge) which carries an important policy signal: communities are not asking for theatre to stop; they are asking for more of it.

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Community Cohesion and Collective Action

The table 6 presents social cohesion and collective action indicators disaggregated by theatre exposure status.

Table 6: Community Cohesion and Collective Action by Theatre Exposure Status (N = 724).

Social Cohesion Indicator	Theatre-Exposed HH	Not Exposed HH
Discussed disaster preparedness with neighbours in past 6 months	74.5%	34.2%
Participated in community clean-up or flood mitigation activity	59.5%	21.5%
Provided assistance to a neighbour during the last disaster event	68.9%	39.8%
Reports a functioning DRR committee active in their community	73.0%	31.0%
High or very high trust in community members to cooperate in disasters	71.6%	43.7%
Mean Social Cohesion Index score (0–10 composite, SD)	7.1 (1.5)	4.4 (1.9)

Source: Author's Field Survey (2026).

Theatre-exposed communities were more than twice as likely to have discussed preparedness with neighbours in the past six months (74.5% versus 34.2%), nearly three times as likely to have participated in collective flood mitigation activity (59.5% versus 21.5%), and substantially more likely to report high trust in neighbours' disaster cooperation (71.6% versus 43.7%). The composite Social Cohesion Index showed a mean difference of 2.7 points (M = 7.1 versus M = 4.4). These findings speak directly to Aldrich and Meyer's (2015) framework, which demonstrates that social capital particularly the bridging ties between groups with different social positions is among the most powerful determinants of how well communities prepare for and recover from disasters.

Sustainability, Challenges, and Enabling Conditions

The table below reports key informant assessments of the sustainability, challenges, and enabling factors associated with community theatre DRR programming in both districts.

Table 7: Sustainability Assessment and Key Challenges — Key Informant Perspectives (n = 30).

Theme / Sub-theme	Proportion Endorsing (%)
Rated current programmes as highly or moderately sustainable	46.7%
Rated sustainability as dependent on continued external NGO funding	80.0%
Believed local theatre groups could sustain independently	26.7%

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Theme / Sub-theme	Proportion Endorsing (%)
Identified formal government integration as necessary for long-term sustainability	90.0%
Lack of sustained financing for performances	93.3%
Inadequate compensation for community actors	76.7%
Limited integration with INGD and government DRR structures	83.3%
Women's participation constrained by social and time barriers	60.0%
Exclusion of persons with disabilities	56.7%
High actor turnover driven by conflict displacement	63.3%
Strong community cultural affinity with local performance traditions	96.7%
High community demand and consistent attendance	90.0%
Youth enthusiasm and capacity as performers	86.7%
Availability of trained facilitators with local-language capability	76.7%

Source: Author's Field Survey (2026).

The sustainability data present a picture that is genuinely mixed in a way that would be obscured by any simple characterisation of the programmes as either successful or failing. The effectiveness evidence is strong, and the community demand data confirm that this effectiveness is recognised and valued by communities. But the institutional support on which these gains depend remains fragile. Eight in ten informants endorsed the view that programme sustainability is contingent on continued external NGO funding. Nine in ten identified formal government integration as the necessary condition for addressing this fragility yet only 46.7% rated current programmes as achieving even moderate sustainability. The constraints identified are specific and actionable: inadequate actor compensation (76.7%), limited INGD integration (83.3%), and insufficient coverage of IDP communities in resettlement sites (73.3%) together constitute a sustainability risk profile that policymakers, donors, and programme designers should take seriously.

Qualitative Findings: Mechanisms, Meanings, and Voices

1. Institutional Perspectives

An INGD representative in Montepuez captured the theatre-governance paradox directly, describing theatre as: "The early warning system that works in the last kilometre, where our official alerts still don't reach." Officials in both districts noted that performances were organised reactively by NGO partners in response to seasonal preparedness windows or post-disaster emergency communication needs, rather than integrated into annual DRR planning calendars or financed through district budget lines, a pattern that Schipper et al. (2014) identify as the primary

structural barrier to the institutionalisation of community-based DRR approaches across sub-Saharan Africa.

2. Theatre Practitioners and the Co-Production Process

Theatre practitioners were insistent, and consistent across both districts, about the centrality of local language and narrative authenticity. A Makua-language facilitator in Montepuez articulated what several practitioners expressed in different ways:

"When people see themselves in the story - not a city person, not an NGO worker, but someone from this community, speaking this language, facing this flood, they understand it is about them and they must act."

This statement describes, in precise experiential terms, what communication scholars mean by narrative identification: the moment at which an audience member recognises themselves in a character and experiences that character's situation as their own, the sense of personal relevance and urgency from which preparedness behaviour follows (Ryan et al., 2020).

3. Women's Voices and Gendered Dimensions

Several women in the Metuge FGD narrated how a performance depicting a female character successfully planning and executing her household's evacuation ahead of flooding had catalysed emergency planning conversations within their own households:

"We watched it together, me and my husband, and afterwards he asked me, 'do we have a plan like that?' We made one that night."

This documents a mechanism, theatrical identification triggering household dialogue, dialogue producing joint planning, planning producing action that connects performance exposure to the preparedness behaviour outcomes in Table 4 through an identifiable social process. It is also a mechanism that no radio broadcast or government alert can replicate, because neither creates the shared experience and social accountability that a performance watched together produces. Women participants also raised barriers that the quantitative data do not fully show: cultural reservations about women performing in public, rehearsal schedules that collide with domestic labour responsibilities, and the absence of women from theatre company leadership and script development roles.

4. Men's Perspectives and Social Belonging

Several participants in Montepuez acknowledged that household emergency planning had been implicitly classified as women's domain, associated with domestic management and therefore beneath the concern of men who understood their role in terms of earning, protection, and community leadership. Performances that depicted male characters demonstrating competent, active disaster leadership within the family had, some felt, made preparedness available as a male identity, not only a female responsibility. In Metuge, men who had been displaced from northern districts described the communal experience of watching a theatre performance as one of the few

occasions on which resettlement had temporarily felt less like displacement and more like belonging:

"It was the first time since we arrived that we truly felt part of the community - not simply observing or waiting, but coming together and participating with others."

This account connects directly to the social cohesion evidence and to finding that collective cultural experience is one of the primary mechanisms through which fractured community identity is reconstructed after displacement.

5. Youth Participants and Embodied Knowledge

Youth participants articulated the educational value of the production process itself:

"When you play the character who loses everything because they didn't evacuate, you learn more about disaster than from any meeting. You live it."

This captures what performance scholars mean by embodied knowledge: understanding that is not simply cognitively registered but felt, enacted, and therefore retained at a qualitatively different depth than information passively received (Singhal et al., 2019).

6. Post-Performance Dialogue as the Critical Mechanism

The combined FGD with DRR volunteers and community theatre actors generated the study's most operationally detailed evidence on what makes performances work. One actor expressed the mechanism connecting emotional experience to practical action directly:

"The performance opens the door. But the discussion after is what makes people walk through it."

This description is consistent with Ryan et al.'s (2020) systematic review, which identifies post-performance community dialogue as the single element most consistently associated with positive preparedness behaviour outcomes across the applied community engagement DRR literature and with Bubeck et al.'s (2024) finding that structured post-performance engagement was the design feature most associated with sustained awareness gains in their Vietnamese coastal communities.

VI. DISCUSSION

Community theatre performance works as a DRR tool in Montepuez and Metuge, and it works substantially better on every measured dimension, than the conventional approaches with which it competes for the limited attention and resources of disaster preparedness programming. The merged effect size of approximately 2.2 standard deviations on the Preparedness Behaviour Scale is not merely statistically significant; it is substantively remarkable, exceeding by a considerable margin the effects typically reported in evaluations of health communication interventions, DRR training programmes, and community awareness campaigns in comparable contexts.

Why Theatre Works: The Mechanism Account

The qualitative evidence converges on an account that is coherent with the participatory communication and critical DRR frameworks outlined in Section 2. Theatre performs, in this

context, because it does three things simultaneously that no other available DRR communication modality does. First, it addresses its audience in their own language and from within their own cultural universe, generating the narrative identification and personal relevance that Tufte (2021), Dutta (2018), and Paton and Johnston (2017) all identify as prerequisites for risk messages to achieve motivational rather than merely cognitive impact. Second, it creates a shared social experience in which community members are constituted as a collective subject rather than as an aggregate of individual information recipients, building the collective efficacy and mutual trust that Aldrich and Meyer (2015) document as the proximate determinants of community preparedness action. Third, through the post-performance facilitation dialogue, it connects the emotional and social experience of performance to specific, household-level behavioural commitments bridging precisely the knowledge-action gap that DRR evaluators so frequently and frustratingly document (Kelman et al., 2020; Ryan et al., 2020; Bubeck et al., 2024).

The Sustainability Challenge

The preparedness gains documented in this study are real, but they are the product of sustained investment by NGO partners and their community theatre collaborators, and the evidence from Table 7 is clear that this investment is more fragile than the gains it has produced. An 80% rate of NGO funding dependency and an 83% identification of limited INGD integration as the central structural gap together constitute a sustainability risk profile that programme designers, donors, and policymakers should take seriously. The finding is consistent with Schipper et al.'s (2014) broader conclusion that government integration is the sine qua non condition for the sustainability of community-based DRR approaches across sub-Saharan Africa.

Gender and Inclusion

Women's enthusiasm for and benefit from theatre programming coexists with women's structural exclusion from the production side of that programming. This matters because, as Desportes and Hilhorst (2020) argue, women's presence in DRR processes as audiences or recipients is not equivalent to their substantive agency in shaping those processes' design and direction. The barriers to women's participation as performers includes cultural restrictions on public performance, rehearsal scheduling that ignores domestic labour demands, male-dominated leadership of theatre companies are not cultural facts that programme designers must accept; they are design problems that targeted investment and deliberate inclusion strategy can address.

VII. KNOWLEDGE CONTRIBUTIONS

This study makes four distinct contributions to the scholarly and practitioner literature on community theatre, DRR communication, and resilience in conflict-affected settings.

The first is empirical scale. With 724 household survey respondents across two contrasting district contexts, this study produces the largest empirically grounded assessment of community theatre as a DRR tool conducted in Cabo Delgado Province. The finding that theatre-based DRR effects

are, if anything, more pronounced in the more severely displacement-affected Metuge context challenges the common assumption that community-based approaches work better in stable, socially cohesive settings (Desportes & Hilhorst, 2020).

The second contribution is mechanistic. This study's integrated qualitative evidence provides what the quantitative data alone cannot: an account of the social and psychological pathways through which theatrical experience translates into preparedness behaviour (Tufte, 2021; Dutta, 2018; Ryan et al., 2020; Singhal et al., 2019; Bubeck et al., 2024).

The third contribution is to the social capital and resilience literature in conflict-displacement settings. This study provides the first quantitatively documented evidence of theatre's social bond reconstruction effect in the specific context of DRR programming in Cabo Delgado.

The fourth contribution is institutional. The governance and sustainability analysis in Table 7 documents with empirical precision the gap between programme effectiveness and institutional integration, and identifies the specific conditions that would need to change for effective theatre-based DRR to achieve institutional sustainability.

VIII. CONCLUSION

This study began with a question about what it takes for a community to act on what it knows about disaster. The evidence gathered in Montepuez and Metuge districts of Cabo Delgado Province from 724 households, 30 key informants, and four focus groups suggests a clear answer: it takes communication that meets communities where they are, in their languages, their cultural forms, their social spaces, and their collective experience of vulnerability. Community theatre, as practised in these two districts over the period covered by this study, demonstrably does this in ways that government alert systems, NGO training programmes, and radio broadcasts structurally cannot.

The evidence for this claim is multi-dimensional and robust. Theatre-exposed households knew more about disaster risk, had taken more preparedness actions, were more socially connected with their neighbours around preparedness, and had greater trust in their community's collective capacity to face disaster than households without theatre exposure on every measured indicator, by large margins, with statistical precision appropriate to a sample of 724. These gains are not yet secure. They depend on continued external financing, on the uncompensated labour of community actors, and on institutional frameworks specifically the relationship between theatre programmes and formal government DRR planning that remain underdeveloped in both study districts. Addressing these structural conditions is the central challenge that this study's findings place before policymakers, donors, and programme designers.

IX. RECOMMENDATIONS

The findings of this study support evidence-based recommendations directed at government institutions, humanitarian actors, donor agencies, and the research community.

1. Rebuild Social Cohesion as the Foundation for Theatre-Based Disaster Resilience
Government institutions, humanitarian agencies, and development partners should invest deliberately in theatre-led community engagement initiatives that treat social cohesion not as a background condition for DRR but as an explicit and measurable programme objective, recognising that communities cannot effectively prepare for or respond to disasters without the social capital that sustained conflict has eroded.

2. Expand Community-Based DRR Learning through Culturally Grounded Theatre
Performance-based learning approaches that use storytelling, role-play, visual demonstration, and structured post-performance dialogue can make complex disaster risk concepts genuinely accessible, particularly among populations with low literacy levels. Future programmes should use theatre to build practical understanding of early warning systems, evacuation planning, household preparedness measures, and community risk reduction actions.

3. Integrate Theatre Performances into Early Warning and Anticipatory Action Mechanisms
Government agencies and humanitarian partners should establish mechanisms that activate community theatre performances during the anticipatory phase of disaster response before shocks occur enabling households to understand the risks ahead of them and take timely protective action.

4. Promote Inclusive and Gender-Responsive Theatre for Disaster Resilience
Theatre programmes should be designed from the outset to incorporate gender-sensitive narratives, actively support women's leadership within performance groups and DRR committees, and remove the practical and social barriers that prevent vulnerable groups from accessing risk information and participating meaningfully in community preparedness planning.

5. Use Theatre Performances to Strengthen Livelihood Resilience and Adaptive Capacity
Performances can communicate practical information on income diversification, climate adaptation, and recovery opportunities in ways that are locally credible and immediately actionable, showcasing successful coping strategies and facilitating community conversations about reducing dependence on climate-sensitive livelihoods.

6. Enhance Community Access to DRR Services and Resources through Theatre-Based Communication
Community theatre can serve as a practical communication bridge between institutions and the communities they are meant to serve, disseminating information about available services, assistance programmes, and community resources in language and formats that displaced populations, returnees, female-headed households, and other hard-to-reach groups can actually understand and act on.

7. Institutionalise Community Theatre within Integrated Disaster Resilience Frameworks
Community theatre should be recognised not as a standalone awareness activity but as a core component of integrated disaster resilience programming. Government agencies, humanitarian organisations, and development partners should formally integrate theatre into disaster preparedness, climate adaptation, peacebuilding, and resilience-building strategies, with dedicated budget lines, standing partnerships with local theatre companies, and pre-agreed activation protocols for the cyclone season and post-disaster response phases.

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Agroecology for Land Restoration and Climate Resilience: Evaluating Farmer-Led Soil Conservation Practices in Post-Cyclone Mecufi District, Cabo Delgado, Mozambique

Henry Omara[1], Mark Kiiza[2]
[1]*Department of Environmental Management, Selinus University of Sciences and Literature Rome-Italy*
[2]*Associate Professor, School of Arts and Social Science Kampala University– Uganda*
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***Abstract*—This study examines agroecology for land restoration and climate resilience by evaluating farmer-led soil conservation practices in post-cyclone Mecufi District, Cabo Delgado Province, Mozambique. The district faces interacting pressures from tropical cyclones, armed conflict, displacement, and soil degradation, which have undermined smallholder agricultural livelihoods and ecosystem resilience. Following Cyclone Kenneth, approximately 87% of cultivated land experienced some degree of cyclone-related soil damage, underscoring the need for locally appropriate restoration strategies. The study employed a documentary review of 74 sources, including peer-reviewed literature, government assessments, NGO evaluations, agricultural extension reports, and community case studies, complemented by primary field observations from 32 farming households. It evaluated the adoption, perceived effectiveness, and enabling conditions of five practices: intercropping and crop diversification, cover cropping, agroforestry integration, contour bunding and soil-water conservation structures, and Farmer-Managed Natural Regeneration. Findings indicate that integrated agroecological practices improve soil fertility, reduce erosion, enhance moisture retention, diversify production, and strengthen household food security. However, adoption remains constrained by inadequate extension services, insecure land tenure, limited access to inputs and finance, and conflict-related displacement. The study recommends integrating farmer-led agroecology into district and national land restoration, disaster recovery, and climate adaptation programmes; strengthening farmer-to-farmer extension and community-based institutions; improving secure land tenure and access to restoration inputs and finance; and prioritising integrated, locally adapted soil and water conservation measures. It concludes that scaling agroecology through an Integrated Agroecological Resilience Framework can simultaneously restore**

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degraded land, strengthen climate resilience, and support sustainable agricultural recovery in cyclone-affected communities of Cabo Delgado province.

***Index Terms*—agroecology; land restoration; soil conservation; climate resilience; post-cyclone recovery; smallholder farmers**

I. INTRODUCTION

Tropical cyclones do not simply destroy crops; they can erode the ecological foundations upon which smallholder agriculture depends. Through intense rainfall, flooding, storm surge, erosion, waterlogging, salinity, and vegetation loss, cyclones can remove fertile topsoil, disrupt soil structure, reduce organic matter, and weaken the capacity of land to sustain production. For smallholder farmers in Mecufi District, Cabo Delgado, who had already been absorbing the structural pressures of poverty, land degradation, and, since 2017, the social fracturing of an armed insurgency, Cyclone Kenneth's landfall on 25 April 2019 was not merely a weather event. Kenneth was the strongest cyclone to hit the African continent and caused extensive damage to agriculture, infrastructure, and livelihoods (UNDP, 2019; Cambaza et al., 2019).

The agricultural consequences were severe and lasting. Cyclone Kenneth destroyed approximately 40,000 homes and displaced an estimated 18,029 people across Cabo Delgado while causing catastrophic damage to agricultural land through storm surge, flooding, soil erosion, saltwater intrusion along the coast, and the physical destruction of standing crops and perennial plantings (UNDP, 2019; Mugabe et al., 2021). In Mecufi District specifically, an estimated 87% of cultivated land sustained some degree of cyclone-related soil damage, ranging from topsoil loss through surface erosion to the longer-term consequences of waterlogging and compaction from storm-surge flooding. What recovery programmes have struggled to address is not the immediate crop loss which is tractable with seed distribution but the underlying soil health crisis that makes each subsequent season more difficult than the last (FAO, 2022; Mondlhane et al., 2025).

Agroecology offers a theoretically grounded and empirically supported alternative to the conventional input-driven recovery paradigm. Rather than treating degraded land as a substrate to be chemically stimulated back to productivity, agroecology treats it as a damaged ecosystem to be ecologically restored through the reintroduction of biological diversity, the rebuilding of soil organic matter, the management of water infiltration, and the integration of trees, shrubs, and herbaceous cover that anchor topsoil and cycle nutrients (Wezel et al., 2020; Bezner Kerr et al., 2021). In sub-Saharan Africa more broadly, agroecological practices including intercropping, agroforestry, cover cropping, contour bunding, and Farmer-Managed Natural Regeneration (FMNR) have demonstrated consistent capacity to restore degraded farmland while improving farmer livelihoods and building resilience to climate shocks (Chomba et al., 2020; Blomme et al., 2023; Birhanu et al., 2024).

This study advances the argument that land restoration and climate resilience are mutually reinforcing outcomes of integrated farmer-led agroecology. Its novelty lies in moving beyond

practice-by-practice assessment to examine how combinations of soil-conservation practices interact with farmer knowledge, community institutions, and enabling conditions to produce restoration and resilience outcomes in a post-cyclone, conflict-affected landscape. While evidence for agroecology is expanding globally, empirical research on these interactions remains limited in northern Mozambique, particularly under conditions where climatic shocks intersect with soil degradation, displacement, and institutional fragility.

The study addresses this gap through a documentary review of 74 sources complemented by field observations from 32 farming households in Mecufi District. It evaluates the adoption, perceived effectiveness, and enabling conditions of five core farmer-led agroecological practices, with particular attention to soil restoration, erosion reduction, agricultural productivity, food security, and climate resilience. The study further examines whether existing agricultural recovery and development interventions adequately recognise the ecological and institutional conditions required for sustained restoration. The central contribution is the development of an Integrated Agroecological Resilience Framework that conceptualises resilience as emerging from synergies among five dimensions: ecological restoration, diversified farming practices, farmer knowledge and agency, community governance, and institutional support. The study therefore reframes post-cyclone agricultural recovery from restoring production to regenerating the ecological capacity for production. It argues that sustainable recovery in Mecufi requires not merely rebuilding what Cyclone Kenneth destroyed, but strengthening the relationships among soil, biodiversity, water, farmers, institutions, and knowledge that determine how agricultural systems withstand future climatic shocks.

Mecufi District occupies the coastal zone of Cabo Delgado Province immediately north of the provincial capital Pemba, bordered to the east by the Indian Ocean, whose warm surface temperatures provide the thermodynamic energy for cyclone intensification that has made this coastline one of the most storm-exposed in eastern Africa (World Bank, 2023). The district supports an estimated population of approximately 97,000 people, the large majority engaged in smallholder rain-fed agriculture producing cassava, maize, cowpea, groundnut, and sesame alongside artisanal fishing and small-scale livestock keeping (INGD, 2024). The district's soils are predominantly Ferralsols and Arenosols which is lateritic, inherently low in organic matter, and highly susceptible to surface erosion when vegetative cover is removed, as cyclone winds and storm surges comprehensively do. Agricultural productivity was constrained even before Kenneth by inadequate extension services, limited market access, and the gradual soil fertility depletion associated with shortened fallow periods and declining crop diversity (Mondlhane et al., 2025; Melo et al., 2025).

Agroecology, as systematised by Wezel et al. (2020) in their landmark review of agroecological principles and elements, is both a science and a practice: a set of ecological principles applied to agricultural systems to produce farming landscapes that function more like diverse natural ecosystems cycling nutrients internally, building organic matter, hosting functional biodiversity, and maintaining hydrological regulation. The ten elements of agroecology identified by the Food and Agriculture Organisation (FAO, 2022) diversity, synergies, efficiency, resilience, recycling,

co-creation of knowledge, human and social values, culture and food traditions, responsible governance, and circular and solidarity economy collectively describe an agricultural paradigm whose outcomes are precisely what Mecufi's degraded post-cyclone landscape most needs. Bezner Kerr et al.'s (2021) systematic review in Global Food Security demonstrated that agroecological approaches improve food security and nutrition outcomes in low- and middle-income countries, with the strongest effects in contexts of high agro-ecological diversity and active community engagement in practice adoption conditions that Mecufi's farming communities can generate when institutional support exists.

The farmer-led natural resource management tradition, exemplified in practice by Farmer-Managed Natural Regeneration (FMNR) as documented by Chomba et al. (2020) across sub-Saharan Africa, positions smallholder farmers not as recipients of externally designed conservation technologies but as custodians of landscape knowledge whose management agency is the primary resource through which degraded land is restored. This tradition challenges like the technocratic impulse in post-disaster agricultural recovery have the tendency to deliver standardised packages of seeds and tools designed by technical agencies and implemented through top-down distribution chains and insists instead that locally adapted, farmer-controlled practices generate better restoration outcomes at lower cost because they draw on contextual ecological knowledge that external agents cannot replicate. Blomme et al. (2023) demonstrated in eastern DR Congo that innovative agroecological packages combining cover crops, minimum tillage, and organic inputs can restore abandoned farmlands in ways that standard soil amendment approaches cannot, generating soil carbon gains, earthworm density improvements, and aboveground carbon stock increases that persist across seasons.

The post-disaster agricultural recovery literature, reviewed by Mondlhane et al. (2025) in the context of southern Mozambique's drought-stricken agricultural systems, documents a persistent pattern: emergency food assistance reaches affected farmers, seed and tool distribution enables planting recovery, and one or two seasons later the recovery programme concludes leaving farmers with replanted fields on soils whose structural damage, erosion losses, and organic matter depletion mean that productivity is lower than pre-disaster levels and declining. Climate-adaptive agricultural recovery, by contrast, explicitly addresses the soil health and ecosystem services dimensions of disaster damage, treating recovery investment as an opportunity to build back with greater climate resilience than existed before the cyclone (Sturridge et al., 2022). The Birhanu et al. (2024) integrated landscape management review (2024) demonstrated that agroecological practices implemented in post-disaster recovery contexts in sub-Saharan Africa generate long-term land restoration benefits including cultivable land expansion from nil to 44% and degraded rangeland reduction from 87% to 28% in specific case sites while simultaneously improving farmer livelihoods and building adaptive capacity to future climate shocks.

II. METHODOLOGY

This study employed a convergent case research design combining a systematic documentary review with primary field observation data. The documentary review methodology, adapted from

Snyder's (2019) systematic narrative approach, was chosen for three reasons: first, the compound crisis context of Mecufi limits the feasibility of large-scale primary surveys due to security constraints and population mobility associated with the ongoing conflict; second, the depth and contextual richness required to understand agroecological adoption dynamics in this setting demands qualitative depth that a purely quantitative design cannot supply; third, the policy-oriented objective of the study requires synthesis across evidence types like agronomic studies, field evaluations, community assessments, and policy documents that are not commensurable within a single primary data collection instrument (Snyder, 2019; Tracy, 2019). The field observation component supplements the documentary review with direct data from 32 purposively selected farming households across four communities in Mecufi District, providing primary evidence on current practice prevalence and perceived effectiveness that the available documentary record does not fully cover. These data do not constitute a representative household survey; they provide contextualising detail and triangulation for the documentary findings and are reported as such throughout the analysis.

III. STUDY AREA

Mecufi District covers an area of approximately 2,070 square kilometres of coastal Cabo Delgado, extending from the Indian Ocean in the east to the upland transition zone in the west. The district's agro-ecological character is shaped by a 1,200–1,400 mm annual rainfall concentrated in the November-to-April rainy season, a hot coastal climate with mean annual temperatures of 26–28°C, and a diverse soil mosaic dominated by sandy Arenosols on the coastal strip and moderately weathered Ferralsols on the inland plateau both inherently infertile and erosion-prone when unprotected. The principal hazards are the annual cyclone risk from the south-west Indian Ocean basin, seasonal flooding along the Mecufi, Ncuale, and Lúrio river floodplains, and episodic drought during El Niño years (INGD, 2024; World Bank, 2023). The four communities selected for field observation where Mecufi Town, Mazeze, Nalope, and Napala which represent the district's agro-ecological diversity across coastal, riverine, and upland contexts.

IV. DATA COLLECTION METHODS

A systematic documentary search was conducted between March and May 2026. Four categories of sources were retrieved and reviewed. First, peer-reviewed academic literature was identified through Web of Science, Scopus, Google Scholar, and the African Journals Online database using search terms including 'agroecology Mozambique', 'soil conservation Cabo Delgado', 'post-cyclone agricultural recovery Mozambique', 'land degradation northern Mozambique', 'FMNR sub-Saharan Africa', 'intercropping soil fertility Africa', and 'climate-smart agriculture smallholder Mozambique'. Second, government documents were retrieved from the Mozambique Instituto Nacional de Gestão e Redução do Risco de Desastres (INGD), the Ministério da Agricultura e Desenvolvimento Rural (MADER), and the Direcção Provincial de Agricultura e Segurança

Alimentar de Cabo Delgado (DPASA). Third, NGO and humanitarian programme evaluations were retrieved from FAO, CARE International, Catholic Relief Services, International Rescue Committee, Aga Khan Development Network, and OCHA's ReliefWeb platform. Fourth, international framework and policy documents from UNEP, FAO, IPCC, and the African Union Commission's Comprehensive Africa Agriculture Development Programme were included. From 187 initially identified records, 74 documents were retained following eligibility screening. Inclusion required: (1) direct relevance to agroecological practices, soil conservation, land restoration, or agricultural recovery in Mozambique or directly comparable sub-Saharan African contexts; (2) publication or production between 2019 and 2025, with foundational pre-2019 literature retained for theoretical grounding; and (3) sufficient methodological transparency to assess reliability. Excluded sources included opinion pieces without empirical grounding, and reports from non-credible outlets.

Field observations were conducted across four communities in Mecufi District between March and May 2026. In each community, eight purposively selected households were visited, chosen to represent variation in cyclone impact severity, land type, gender of household head, and presence or absence of NGO agroecological programming. At each household, a structured observation checklist was completed documenting: visible evidence of soil conservation structures (contour bunds, vetiver grass strips, half-moon bunds); presence of agroforestry trees on agricultural plots; crop diversity and intercropping arrangements; surface soil condition (crusting, erosion rills, mulch coverage); and household-reported practice adoption. Semi-structured interviews of 30–45 minutes with the primary farm decision-maker complemented the observational data, covering farming history, cyclone impact, practice adoption history, and perceived outcomes. Six key informant interviews were conducted with district extension officers, NGO field staff, and community leaders to contextualise household-level findings within the institutional landscape.

V. DATA ANALYSIS

Documentary data were analysed through thematic framework analysis (Tracy, 2019) organised around the five agroecological practice domains and three cross-cutting analytical themes: adoption enablers and constraints, biophysical effectiveness, and institutional alignment. Two researchers coded all documents independently; disagreements were resolved through structured consensus review. Quantitative data from documentary sources yield comparisons, erosion rates, adoption percentages were extracted into a standardised matrix and descriptively synthesised; formal meta-analysis was not attempted given the heterogeneity of study contexts and measurement approaches.

Field observation data were entered into a structured database and analysed descriptively, with frequency tables and cross-tabulations used to characterise practice prevalence, household variation, and perceived effectiveness. Qualitative interview data were transcribed and analysed

thematically through NVivo 14. Documentary and field data were formally integrated through a convergence matrix in which each documentary theme was cross-checked against field observation evidence, with any divergences explicitly documented and explored. The integrated synthesis informed the development of the Integrated Agroecological Resilience Framework presented under results section.

VI. ETHICAL CONSIDERATIONS

This study operated in a context of post-cyclone, conflict-affected, highly displacement-affected Mecufi District that imposes ethical obligations beyond those of standard agronomic field research. Communities in the study area have experienced compounding violations of their wellbeing through cyclone damage, insurgent violence, forced displacement, and the repeated arrival of researchers and programme evaluators whose work has not consistently produced benefits for the communities studied. The research team took four specific steps to mitigate the ethical risks arising from this history.

First, all household participation was voluntary; informed consent was obtained verbally at the outset of each interaction, with a plain-language explanation of the study's purpose, voluntary nature, and the researchers' institutional affiliation provided in Portuguese and Makua. No material inducements were offered for participation. Second, community leaders in all four communities provided collective consent before household visits began, following consultation about the study's purpose and expected outputs. Third, given the active conflict environment in adjacent districts and the presence of IDPs among the study population, the field team coordinated all movements with the district administration and NGO partners operating in the area, and no research activities were conducted in areas assessed as presenting security risks to participants or the research team. Fourth, all data were anonymised at collection; no individual or household identifiers are retained in the analysis or reporting. Community leaders were offered an opportunity to review and comment on a summary of findings before finalisation, a practice consistent with the ethical framework articulated by Israel and Hay (2006) for socially sensitive research in vulnerable community contexts.

VII. LIMITATIONS OF THE STUDY

Four limitations constrain the scope and confidence of this study's findings and must be stated directly. First, the field observation sample of 32 households across four communities is too small and purposively selected to support generalisation to Mecufi District as a whole, let alone to Cabo Delgado Province. The field data provide contextual depth and triangulation for documentary findings; they do not constitute a representative household survey and should not be read as such. Second, the documentary evidence base on Mecufi District specifically is thin: most peer-reviewed agroecological research from Mozambique focuses on southern and central provinces, meaning

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that key findings are extrapolated from comparable but not identical contexts like Malawi, Tanzania, DR Congo, and Zimbabwe whose agro-ecological and socio-institutional conditions differ from northern Mozambique's in ways that limit direct transfer. Third, the active conflict in adjacent districts constrained the geographic scope of field visits; communities closest to the most severely conflict-affected zones were not accessible, creating a potential selection bias toward communities with greater stability and, possibly, better agricultural recovery trajectories. Fourth, the study's cross-sectional design captures the state of agroecological adoption at a single point in time and cannot establish causal attribution of improved soil outcomes to specific practices; longitudinal data collection would be necessary to make credible before-after comparisons.

VIII. RESULTS

The findings present the distribution of the 74 retained documentary sources across source type and thematic focus. Peer-reviewed literature accounted for the largest share (36.5%), followed by NGO programme evaluations (25.7%), government and intergovernmental reports (24.3%), and framework documents (13.5%). Soil conservation and agroforestry were the most frequently addressed thematic domains across source types.

Table 1: Distribution of Retained Documentary Sources

Source Category	Number	% of 74	Primary Thematic Focus
Peer-reviewed academic articles	27	36.5%	Agroecology principles; soil health; SSA land restoration
NGO / INGO programme evaluations	19	25.7%	Post-disaster recovery; agricultural livelihoods; Mozambique
Government and intergovernmental reports	18	24.3%	Post-Kenneth recovery; national agriculture policy; INGD
International framework documents	10	13.5%	Sendai Framework; African Union CAADP; FAO agroecology
TOTAL	74	100.0%	

Source: Author's Document Review (2026).

Land Degradation and Cyclone Impact in Mecufi District

Table 2 synthesises the documentary and field evidence on agricultural land degradation and cyclone impact across Mecufi District, drawing on INGD (2024), UNDP (2019), and FAO (2022) assessments alongside field observation data. The scale of cyclone-related land degradation provides the foundational context within which agroecological recovery must operate.

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Table 2: Agricultural Land Degradation and Cyclone Impact Indicators

Land Degradation Indicator	Estimated Scale / Severity	Primary Data Source	Field Observation Corroboration
Agricultural land with cyclone-related soil damage (2019)	~87% of cultivated area	UNDP (2019); INGD (2024)	Confirmed across all 4 communities
Topsoil loss through surface erosion (post-Kenneth)	High severity in 68% of surveyed plots	FAO (2022); Field data (2025)	Erosion rills visible in 21 of 32 HH plots
Saltwater intrusion affecting coastal farm plots	Moderate to severe in coastal zone	Mugabe et al. (2021)	Confirmed in Mecufi Town community
Soil organic matter depletion — pre-existing trend	Moderate to severe province-wide	Melo et al. (2025)	Reported by all 6 extension informants
Farmer-reported productivity decline since Kenneth	Mean 42% decline	Field data (2025); FAO (2022)	Consistent across all household interviews
Agricultural plots with visible erosion control structures	28% of surveyed plots	Field data (2025)	Contour bunds, grass strips observed
Agricultural plots with agroforestry tree integration	34% of surveyed plots	Field data (2025)	Predominantly Moringa, Gliricidia, Faidherbia

Sources: UNDP (2019); FAO (2022); INGD (2024); Mugabe et al. (2021); Field observation data (2026).

Agroecological Practice Adoption - Prevalence and Profile

Table 3 presents the prevalence of the five core agroecological practice domains across the 32 observed farming households, cross-tabulated by gender of primary farm decision-maker, IDP versus host community status, and exposure to NGO agroecological programming. These data reveal significant variation in adoption rates across practice types and household characteristics.

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Table 3: Agroecological Practice Adoption by Household Category

Agroecological Practice	Overall Adoption n/32 (%)	Male-Headed HH n/19 (%)	Female-Headed HH n/13 (%)	IDP HH n/9 (%)	Host Community HH n/23 (%)	NGO Programme HH n/14 (%)	Non-Programme HH n/18 (%)
Intercropping / crop diversification	26 (81.3%)	15 (78.9%)	11 (84.6%)	6 (66.7%)	20 (87.0%)	13 (92.9%)	13 (72.2%)
Cover cropping (legume or grass)	17 (53.1%)	9 (47.4%)	8 (61.5%)	3 (33.3%)	14 (60.9%)	11 (78.6%)	6 (33.3%)
Agroforestry tree integration	11 (34.4%)	7 (36.8%)	4 (30.8%)	1 (11.1%)	10 (43.5%)	9 (64.3%)	2 (11.1%)
Contour bunding / soil-water structures	9 (28.1%)	6 (31.6%)	3 (23.1%)	1 (11.1%)	8 (34.8%)	8 (57.1%)	1 (5.6%)
Farmer-Managed Natural Regeneration (FMNR)	7 (21.9%)	5 (26.3%)	2 (15.4%)	0 (0.0%)	7 (30.4%)	6 (42.9%)	1 (5.6%)
Adopting ≥3 practices simultaneously	14 (43.8%)	8 (42.1%)	6 (46.2%)	1 (11.1%)	13 (56.5%)	12 (85.7%)	2 (11.1%)

Source: Author's Field Observation Data (2026). HH = Household; IDP = Internally Displaced Person.

Several patterns in Table 3 deserve particular attention. Intercropping and crop diversification showed the highest overall adoption rate (81.3%), reflecting its low capital requirement, compatibility with subsistence production logic, and alignment with traditional Makua farming systems that historically maintained diverse cropping arrangements before cyclone damage simplified agricultural systems under food emergency pressures. Cover cropping adoption at 53.1% overall masks a striking differential: households participating in NGO agroecological programmes adopted cover crops at 78.6% more than double the 33.3% rate among non-

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programme households. This gap is even more pronounced for agroforestry integration (64.3% versus 11.1%) and FMNR (42.9% versus 5.6%), suggesting that these more technically demanding and longer-payback practices depend heavily on external support for initial adoption. The near-zero adoption rates for all practices among IDP households (with the exception of intercropping at 66.7%) reflect the fundamental constraint of land tenure insecurity for people farming plots to which they have no secure access, a structural barrier that no amount of extension advice or seed provision can overcome.

Agroecological Practice Effectiveness - Perceived and Documented Outcomes

Table 4 synthesises farmer-perceived effectiveness data from field interviews alongside documented outcomes from comparable programme evaluations in the documentary review. Farmer-perceived data from 26 households that had adopted at least one practice for two or more seasons are reported alongside the documentary evidence.

Table 4: Agroecological Practice Effectiveness - Farmer Perceptions and Documentary Evidence.

Practice	Farmers Reporting Positive Soil/Yield Outcomes (n/adopters, %)	Mean Farmer-Reported Yield Change (%)	Documented Outcomes - Comparable Studies	Key Documentary Source
Intercropping / crop diversification	22/26 (84.6%)	+ 23% vs monoculture	Yield increases 15–35%; soil N improvement	Bezner Kerr et al. (2021); Dagunga et al. (2023)
Cover cropping (legume/grass)	14/17 (82.4%)	+ 18% following season	Soil OM +12–28%; erosion reduction 30–50%	Blomme et al. (2023); Birhanu et al. (2024)
Agroforestry tree integration	9/11 (81.8%)	+ 31% over 3 seasons	Carbon stock +370%; soil fertility improvement	Chomba et al. (2020); Blomme et al. (2023)
Contour bunding / SWC structures	8/9 (88.9%)	Reduced post-rain erosion (qualitative)	Cultivable land increase nil → 44% in SSA cases	Birhanu et al. (2024)

Practice	Farmers Reporting Positive Soil/Yield Outcomes (n/adopters, %)	Mean Farmer-Reported Yield Change (%)	Documented Outcomes - Comparable Studies	Key Documentary Source
FMNR	6/7 (85.7%)	+ 27% vs non-FMNR plots	Livelihood value: $182–$378/HH/year	Chomba et al. (2020)
≥3 practices combined	13/14 (92.9%)	+ 38% cumulative effect	Degraded farmland recovery: superior outcomes	Blomme et al. (2023)

Source: Author's Field Data (2026) combined with documentary review.

The high farmer-perceived effectiveness rates across all practice types ranging from 81.8% for agroforestry to 92.9% for multi-practice combinations should be read with appropriate methodological caution: these are perceptions from early adopters who have maintained practices for two or more seasons, a group likely to be positively selected toward those who saw initial results. Nevertheless, the alignment between farmer-perceived outcomes and the documented evidence from comparable studies strengthens confidence that the practices are generating real agronomic benefits. The striking finding is the cumulative effect of multi-practice adoption: households combining three or more agroecological practices reported a mean perceived yield improvement of 38% relative to their pre-agroecology baselines substantially higher than any single practice in isolation consistent with Blomme et al.'s (2023) finding that innovative agroecological packages generate soil restoration outcomes superior to any single practice applied alone.

Enabling Conditions and Constraints

Table 5 presents the enabling conditions and constraints identified across documentary and field sources. Key informant interviews provided the most operationally detailed evidence on institutional constraints.

Table 5: Enabling Conditions and Constraints for Agroecological Practice Adoption

Factor	Category	Prevalence - HH Reports n/32 (%)	Key Documentary Corroboration
NGO programme participation	Enabler	14 (43.8%)	Birhanu et al. (2024); FAO (2022)

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Factor	Category	Prevalence - HH Reports n/32 (%)	Key Documentary Corroboration
Secure land tenure	Enabler	21 (65.6%) — of which only 8 (38%) have documented tenure	Melo et al. (2025); Feijó et al. (2022)
Access to extension services	Enabler	12 (37.5%)	Mondlhane et al. (2025); INGD (2024)
Traditional ecological knowledge	Enabler	29 (90.6%)	Wezel et al. (2020); Chomba et al. (2020)
Farmer-to-farmer learning	Enabler	23 (71.9%)	Chomba et al. (2020); Dagunga et al. (2023)
IDP / displacement status	Constraint	9 (28.1%) IDP	Sturridge et al. (2022); OCHA (2025)
Land tenure insecurity	Constraint	24 (75.0%)	Melo et al. (2025); Feijó et al. (2022)
Inadequate access to seeds/planting material	Constraint	21 (65.6%)	FAO (2022); Blomme et al. (2023)
Labour scarcity (conflict, male outmigration)	Constraint	18 (56.3%)	Sturridge et al. (2022); Mugabe et al. (2021)
Limited extension support for agroecology	Constraint	26 (81.3%)	INGD (2024); Mondlhane et al. (2025)
Market access for diverse crops	Constraint	22 (68.8%)	FAO (2022); Feijó et al. (2022)

Source: Author's Field Data (2026) combined with documentary review.

The constraint profile reveals a systemic pattern that goes beyond individual farmer capacity or motivation. Land tenure insecurity, identified as a constraint by 75% of surveyed households, is the foundational barrier: farmers who do not have secure rights to the land they cultivate have no rational incentive to invest in practices whose returns materialise over multiple seasons. Agroforestry planting, contour bund construction, and FMNR all require multi-year investment horizons that are irrational for households on insecure tenures. Limited extension support for

specifically agroecological practices (identified by 81.3% as a constraint) reflects the broader institutional context in which Mozambique's agricultural extension system remains oriented toward conventional variety-fertiliser recommendations rather than agroecological systems thinking. The striking enabling role of traditional ecological knowledge (90.6%) is perhaps the most analytically significant finding: the vast majority of farmers identified their pre-existing understanding of local soils, seasonal patterns, and plant-soil interactions as a primary resource for practice adoption suggesting that agroecological extension need not start from zero but can build on and systematise knowledge already present in communities.

The Integrated Agroecological Resilience Framework (IARF)

Drawing on the convergent evidence from documentary and field data, Table 6 presents the Integrated Agroecological Resilience Framework (IARF) for post-cyclone land restoration in Mecufi and comparable coastal Cabo Delgado contexts. The IARF organises intervention priorities across five strategic domains.

Table 6: Integrated Agroecological Resilience Framework (IARF) for Post-Cyclone Mecufi District.

IARF Domain	Core Objective	Priority Practices	Policy Entry Points
1. Soil Health Restoration	Rebuild organic matter, structure, and biological activity	Intercropping + cover crops + organic inputs	Agricultural extension redesign; NGO programme alignment
2. Erosion Control and Water Management	Reduce topsoil loss and improve rainfall infiltration	Contour bunding + vetiver strips + half-moon bunds	District land management planning; community labour programmes
3. Agroforestry and Biomass Integration	Restore tree cover, nutrient cycling, and microclimate	FMNR + targeted agroforestry planting + green manures	Tree seed distribution; farmer group propagation nurseries
4. Tenure and Governance	Secure land rights and community resource management institutions	Community land demarcation; WUAs; conflict-sensitive tenure	Land administration reform; community para-legal services
5. Knowledge and Extension	Build farmer capacity and institutional recognition of local knowledge	Farmer field schools; peer learning; extension redesign	National extension curriculum reform; NGO-government co-learning

Source: Author's synthesis (2026).

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IX. DISCUSSION

The findings synthesised across 74 documentary sources and 32 field-observed farming households produce a picture of agroecological land restoration in post-cyclone Mecufi that is simultaneously more encouraging and more structurally troubled than either optimistic donor narratives or pessimistic assessments of recovery failure typically acknowledge. The encouragement lies in the evidence itself: farmers who have adopted even a single agroecological practice report measurable soil and productivity improvements with 82–89% consistency, and those combining three or more practices report cumulative yield improvements of 38% relative to their pre-agroecology baselines. The dramatic differential between NGO-programme households and non-programme households with multi-practice adoption at 85.7% versus 11.1% establishes beyond reasonable doubt that the practices are feasible, affordable, and desirable for Mecufi farmers when the enabling support exists.

The structural trouble lies in what that enabling-condition gap represents. An 81.3% rate of inadequate extension support for agroecology tells us that the district's agricultural support infrastructure is not currently designed to deliver the kind of practice-specific facilitation that moves farmers from awareness of a technique to confident adoption of it. A 75% rate of land tenure insecurity tells us that the overwhelming majority of surveyed households face a rational disincentive to invest in multi-season practices whose returns they may not be able to claim. And the near-zero adoption rates among displaced households who constitute 28.1% of the study sample and a far larger proportion of Mecufi's agricultural population in the post-Kenneth, post-insurgency context tells us that the farmers with the greatest exposure to soil degradation are systematically excluded from the recovery pathway that agroecological restoration represents.

The knowledge-enabler finding deserves particular emphasis because it points toward a recovery strategy that is simultaneously more respectful of community agency and more cost-effective than the technocratic alternative. When 90.6% of surveyed farmers identify traditional ecological knowledge as an enabling resource for agroecological practice adoption, they are describing a repository of contextual wisdom about local soils, seasonal patterns, and plant-soil interactions that decades of research have documented as a primary asset in agroecological transitions (Wezel et al., 2020; Bezner Kerr et al., 2021). An extension approach that treats farmers as blank recipients of externally designed technologies will systematically underperform relative to one that builds on, systematises, and collectively validates the ecological knowledge that farming communities already possess. Farmer field schools and peer learning networks, the approaches that have generated the strongest evidence for durable agroecological adoption across sub-Saharan Africa (Chomba et al., 2020; Dagunga et al., 2023) are precisely the extension modalities that operationalise this insight.

The conflict dimension of Mecufi's crisis must not be reduced to a background condition. The labour scarcity that 56.3% of households identified as a constraint is not merely a demographic feature; it reflects the systematic male outmigration driven by both conflict displacement and security concerns, leaving female-headed households who constitute 40.6% of the study sample

managing farming systems with reduced family labour at precisely the moment when multi-practice agroecological adoption demands the greatest labour investment. The finding that female-headed households show equal or marginally higher adoption rates for cover cropping (61.5% versus 47.4%) and similar rates for intercropping (84.6% versus 78.9%) demonstrates that women farmers are motivated and capable practitioners of agroecological approaches but the practice combinations requiring the heaviest labour investment, particularly contour bunding (23.1% versus 31.6%) and FMNR (15.4% versus 26.3%), show lower female adoption rates that point directly to labour constraint rather than knowledge or motivation deficits (Bezner Kerr et al., 2022; Desportes & Hilhorst, 2020).

X. CONCLUSION

The land that smallholder farmers in Mecufi District are trying to restore is not, in the final analysis, merely a physical substrate. It is the material foundation of food security, livelihood stability, cultural continuity, and social resilience for communities that have absorbed an extraordinary sequence of shocks like cyclone, conflict, displacement, poverty without the institutional support that the scale of those shocks demands. The agroecological practices documented in this study represent these communities' most accessible pathway to restoring that foundation, and the evidence assembled from 74 documentary sources and 32 farming households demonstrates that the pathway is real, feasible, and already being walked by farmers who have found ways to adopt and sustain agroecological approaches despite the barriers that structural neglect, tenure insecurity, and inadequate extension have placed before them.

What this study cannot conclude and what must not be allowed to obscure the findings above is that those barriers are incidental or easily overcome. A 75% rate of land tenure insecurity is not a problem that agroecological extension can fix. An 81.3% rate of inadequate extension support for agroecology is not something that farmer motivation and traditional knowledge alone can compensate for. Zero adoption of FMNR among displaced households is not a farmer capacity problem; it is a land rights problem that requires political and institutional action. The Integrated Agroecological Resilience Framework proposed in this study names these structural enablers explicitly, because a framework that omits them would be analytically incomplete and operationally useless: agroecological practices work when the conditions for their adoption exist; creating those conditions is the policy problem that Cabo Delgado's recovery agenda has not yet adequately solved.

The communities of Mecufi are not waiting passively for that solution. They are, with the knowledge they carry and the land they can access, already practising the restoration of a landscape that climate change and human-made crisis have damaged. What they need from government, from NGOs, from international donors, and from researchers, is not more information about what to do, they know what to do. They need secure rights to the land on which to do it, extension services that can facilitate and scale what they already know, and institutional frameworks that recognise

farmer-led agroecological restoration as climate adaptation, as disaster recovery, and as development.

XI. IMPLICATIONS OF THE STUDY

Theoretical Implications

This study makes three contributions to the theoretical and empirical literature on agroecological transitions, post-disaster agricultural recovery, and climate adaptation in conflict-affected African contexts. First, it demonstrates that the enabling-condition gap is the differential between households with NGO programme support and those without is the primary determinant of agroecological adoption in post-cyclone Mecufi, more significant than farmer knowledge, motivation, or resource endowment. This finding has implications for theories of agroecological transition that locate the primary barrier in farmer agency rather than institutional environment (Wezel et al., 2020). Second, it provides the first field-observation evidence of agroecological adoption rates and perceived effectiveness in the specific compound crisis context of post-Kenneth Cabo Delgado, extending the literature base beyond the central and southern Mozambique contexts in which most existing research is concentrated. Third, the labour-constraint finding for female-headed households showing lower adoption of labour-intensive practices despite equal or higher motivation contributes to the feminist political ecology literature on gendered barriers to agroecological transitions in conflict-affected settings (Bezner Kerr et al., 2022; Desportes & Hilhorst, 2020).

Policy Implications

For the Government of Mozambique and the Ministério da Agricultura e Desenvolvimento Rural, the findings provide empirical justification for: redesigning the agricultural extension service in Cabo Delgado around agroecological principles rather than conventional input recommendations; allocating dedicated budget lines in the provincial agricultural recovery plan for farmer field schools and peer learning networks; and prioritising community land demarcation in cyclone-affected districts as a precondition for investment in agroecological land restoration. For international NGOs and humanitarian donors, the findings argue for extending programme timeframes to match the multi-season investment horizon required by agroecological practices, and for integrating land tenure security into agricultural recovery programme design as a structural prerequisite rather than a background assumption.

XII. RECOMMENDATIONS

Redesign the provincial agricultural extension service in Cabo Delgado around agroecological systems thinking, recruiting and training extension agents in soil-biological principles, multi-practice agroecological design, and farmer field school facilitation replacing the conventional variety-fertiliser paradigm that current extension practice embodies. Allocate dedicated budget

lines within the Post-Kenneth Recovery Plan and the national Disaster Risk Reduction framework specifically for community-level agroecological restoration activities, recognising these as climate adaptation investments rather than welfare programmes. Prioritise community land demarcation and formalised land use planning in Mecufi and adjacent coastal districts, treating secure tenure as the precondition for agroecological investment rather than a long-term aspiration.

Extend agroecological programme timeframes to a minimum of five years, accepting that practices with multi-season payback periods cannot be meaningfully adopted, evaluated, or sustained within two- or three-year project cycles. Integrate land tenure support such as community para-legal services, land demarcation assistance, and advocacy for IDP land rights into agroecological recovery programming as a structural component rather than a separate thematic area. Prioritise women farmers' access to labour-saving technologies, communal work arrangements, and child-care provision as explicit components of agroecological programme design, recognising that labour scarcity is a gendered constraint that standard programme designs systematically fail to address. Fund farmer-to-farmer learning networks and seed multiplication groups as the most evidence-based and cost-effective modality for scaling agroecological adoption in post-cyclone communities, building on the 71.9% rate of farmer-to-farmer learning already documented in Mecufi.

Prioritise longitudinal primary research in Mecufi and comparable northern Mozambique coastal districts, collecting soil health data like organic carbon, bulk density, aggregate stability, infiltration rates at baseline, two years, and five years post-adoption to generate the credible before-after attribution evidence that cross-sectional studies cannot provide. Commission participatory action research that co-designs agroecological restoration protocols with Mecufi farming communities, building on and systematising the traditional ecological knowledge that 90.6% of surveyed farmers identified as an enabling resource. Develop and validate the IARF through structured piloting across at least three contrasting agro-ecological zones in Cabo Delgado, generating the contextual adaptation evidence needed to scale framework recommendations beyond the coastal zone contexts in which the current study's field data were collected.

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The Influence of Digital Marketing on Teenage Consumer Preferences a Sustainable Development Perspective

[1]Vaishali Agrahari, [2]Dr. Ambrish
[1]Research Scholar, University of Lucknow
[2]Assistant Professor, Shia P. G. College, Lucknow
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***Abstract*—Digital marketing has become a central force in shaping teenage consumer preferences in the modern global economy. Teenagers are one of the most dynamic consumer groups, with significant purchasing power and influence over household decisions. This research explores the influence of digital marketing strategies on teenage consumer preferences, placing special emphasis on sustainability and the broader goals of sustainable development. It investigates the role of social media, influencer culture, and digital advertisements in shaping teenagers' decisions, while examining the extent to which ecofriendly and ethical messages impact purchasing choices. The study adopts a mixed method approach, drawing insights from primary surveys of teenagers and secondary data from academic journals and reports. Findings reveal that while digital marketing strongly impacts teenage consumer behavior, sustainability is often a secondary concern unless effectively communicated through creative and authentic campaigns. The paper concludes with suggestions for businesses, policymakers, and educators to foster sustainable consumerism among teenagers through responsible and innovative marketing practices.**

***Index Terms*—Digital Marketing, Teenage Consumer Psychology, Sustainable Development, Consumer Preferences, Social Media Influence, Green Marketing**

I. INTRODUCTION

Digital marketing is a fast-growing component of global trade and consumer behavior, significantly influencing how teenagers make consumption-related decisions. In the digital era, teenagers are highly active on social media platforms such as Instagram, YouTube, TikTok, and Facebook, where they encounter multiple marketing messages daily. As a result, their preferences and buying patterns are shaped not only by traditional advertising but also by peer influence, celebrity endorsements, and interactive digital content.

Teenagers represent a crucial consumer segment because they are early adopters of trends, highly receptive to digital innovation, and likely to carry their preferences into adulthood. Moreover, with increasing awareness of environmental and social issues, sustainable development has become a global priority. The Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production, emphasize the need to shift consumer behavior towards sustainability. Understanding teenage psychology in this context is essential for aligning marketing strategies with sustainable practices.

This paper investigates the intersection of digital marketing, teenage consumer psychology, and sustainable development. It examines how digital platforms create preferences, how teenagers respond to sustainability-oriented marketing, and what strategies can promote long-term responsible consumption.

II. REVIEW OF LITERATURE

A wide range of literature highlights the importance of digital marketing in shaping consumer preferences, especially among teenagers.

1. Djafarova and Trofimenko (2019) found that Instagram influencers significantly impact teenage girls' buying behavior, especially for fashion and beauty products.
2. Evans, Phua, Lim, and Jun (2017) argued that influencer endorsements increase product trust and brand credibility among younger audiences.
3. 1. Kotler and Keller (2016), digital marketing represents a paradigm shift in business-to-consumer communication, where engagement, personalization, and interactivity have become central. Teenagers, often considered digital natives, respond more positively to online engagement compared to traditional marketing methods.
4. McNeill and Moore (2015) highlighted that while young consumers are aware of environmental issues, their purchasing decisions often prioritize style, affordability, and brand image over sustainability concerns.
5. Kaplan and Haenlein (2010) argue that social media platforms facilitate two-way communication between brands and consumers, allowing marketers to build trust and credibility. Teenagers, who are often influenced by peer validation and social identity, are particularly responsive to such marketing.
6. Nadaraja and Yazdanifard (2013) supports this, noting that social media significantly affects brand perception among youth.
7. Solomon (2018) explains that teenagers often exhibit a mix of emotional and rational decision-making. Emotional appeals, including celebrity endorsements and visually engaging advertisements, tend to drive their preferences. Rational factors such as price, quality, and sustainability also play a role but are secondary in many cases.
8. John (2016) and Belk (2013) further illustrate that teenagers' identities are closely tied to their consumption patterns.

9. Peattie and Crane (2005) emphasize the need for authentic green marketing practices to avoid skepticism. Teenagers may express interest in sustainable products but often lack the purchasing power to prioritize them.
10. White, Habib, and Hardisty (2019), effective sustainability messages combined with affordability can motivate teenagers to choose eco-friendly options.
11. Ajzen (1991) provides insights into how attitudes, subjective norms, and perceived behavioral control influence teenage decision-making.

The literature highlights gaps in understanding how sustainability is integrated into digital marketing campaigns aimed at teenagers. While previous studies explore digital engagement and consumer psychology, fewer examine the link between digital marketing, teenage behavior, and sustainable development. This study seeks to address this gap by combining insights from marketing, psychology, and sustainability research.

III. RESEARCH OBJECTIVES

1. To study the influence of digital marketing on teenage consumer preferences.
2. To analyze the impact of sustainability-oriented messages in shaping teenage purchase decisions.
3. To evaluate the role of social media and influencer culture in teenage consumer psychology.
4. To suggest strategies for integrating sustainability into digital marketing campaigns targeting teenagers.

IV. RESEARCH GAP

While several studies have examined digital marketing's role in shaping consumer preferences (Kotler & Keller, 2016; Kaplan & Haenlein, 2010), and others have explored teenage consumer psychology (John, 2016; Belk, 2013), very few have integrated these two areas with a sustainable development perspective. Most prior studies have focused either on the effectiveness of digital campaigns or on teenagers' buying behavior, but not on how sustainability-oriented marketing messages specifically influence teenagers' preferences in the digital space. Additionally, much of the literature has been conducted in Western contexts, with limited empirical evidence from developing countries like India, where teenagers represent a rapidly growing and highly active digital consumer segment. This creates a gap in understanding how digital marketing strategies can promote sustainable consumerism among teenagers, especially in emerging economies.

V. HYPOTHESES

Based on the objectives and literature, the following hypotheses are proposed:
H1: Digital marketing significantly influences teenage consumer preferences.

H2: Sustainability-oriented marketing messages positively affect teenagers' attitudes toward eco-friendly products.
H3: Social media influencers have a stronger impact on teenage consumer choices compared to traditional digital advertisements.
H4: Peer influence mediates the relationship between digital marketing exposure and teenage purchasing decisions.
H5: Cost and accessibility moderate the relationship between sustainability awareness and actual purchase behavior among teenagers.

VI. RESEARCH METHODOLOGY

This study adopts a descriptive and analytical research design. Both primary and secondary data were utilized to gain a holistic understanding of the research problem. Primary data was collected through structured surveys and interviews with teenagers aged 13 to 19 in urban and semi-urban areas. The survey included questions on digital media usage, brand preferences, awareness of sustainability, and influence of digital marketing. Stratified random sampling was employed to ensure representation across age groups, gender, and socio-economic backgrounds. A total of 200 respondents participated. Secondary data was drawn from academic journals, books, market research reports, and online resources. Statistical tools such as chi-square test, correlation, and regression analysis were applied to analyze the quantitative data. Qualitative responses were coded and thematically analyzed to identify patterns and insights.

VII. ANALYSIS AND DISCUSSION

The analysis revealed that digital marketing strongly influences teenage consumer preferences. More than 70% of respondents admitted that social media advertisements and influencer endorsements affected their product choices. Fashion, technology, and food products were the top categories influenced by digital marketing. Peer influence was a significant factor, as teenagers were more likely to purchase products popular among their friends or trending on social media.
When asked about sustainability, nearly 60% of teenagers expressed awareness of ecofriendly products, but only 35% regularly purchased them. The gap suggests that while awareness exists, affordability and accessibility are barriers. Teenagers reported that brands promoting sustainability through engaging and authentic campaigns—such as ecofriendly packaging or social responsibility initiatives—were perceived more positively. However, skepticism arose when brands were perceived to exaggerate their claims, a phenomenon often described as 'greenwashing'.
Regression analysis indicated that emotional appeals had a stronger effect on consumer preferences compared to rational factors such as price and sustainability. However, when sustainability messages were integrated into emotional campaigns (e.g., using influencers to promote eco-friendly lifestyles), the impact was significantly higher.

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VIII. DATA COLLECTION OVERVIEW

A survey of 200 teenagers (aged 13–19) was conducted in Prayagraj using stratified random sampling. The questionnaire included questions on digital media usage, purchasing behavior, awareness of sustainability, and influence of digital marketing.

Table 1: Demographic Profile of Respondents (N=200)

Variable	Category	Frequency	Percer
Gender	Male	108	54.0
	Female	92	46.0
Age Group	13–15 years	65	32.5
	16–17 years	80	40.0
	18–19 years	55	27.5
Residence	Urban	120	60.0
	Semi-Urban	80	40.0

Table 2: Influence of Digital Marketing Channels

Digital Marketing Channel	Highly Influential (%
Social Media Ads (Instagram, TikTok, YouTube)	72
Influencer Endorsements	68
Online Brand Websites	45
Email & SMS Campaigns	25

IX. STATISTICAL METHODS APPLIED

1. Chi-Square Test – To test the association between gender and preference for influencer marketing.

Result: $\chi^2 = 12.45$, $p < 0.05 \rightarrow$ Significant association found; female teenagers were more influenced by fashion/beauty influencers than male teenagers.

2. Correlation Analysis – To examine the relationship between time spent on social media and likelihood of purchasing recommended products.

Result: $r = 0.62$ (strong positive correlation).

3. Regression Analysis – To test the impact of sustainability messages and peer influence on purchase intention.

Model Summary: $R^2 = 0.54 \rightarrow$ 54% of variance in purchase intention explained by sustainability and peer influence.

Peer influence had a stronger beta coefficient ($\beta = 0.45$) compared to sustainability messages ($\beta = 0.32$).

X. FINDINGS

1. Digital marketing has a strong influence on teenage consumer behavior, particularly through social media platforms.
2. Peer influence and social validation play a crucial role in teenagers' purchasing decisions.

3. While sustainability awareness is high among teenagers, actual sustainable consumption is limited by cost and accessibility.
4. Emotional marketing strategies are more effective than purely rational ones; however, combining sustainability with emotional appeals enhances effectiveness.
5. Teenagers are skeptical of brands that engage in greenwashing, indicating the importance of authenticity in marketing campaigns.

XI. CONCLUSION

The study concludes that digital marketing is a powerful driver of teenage consumer preferences, with social media and influencer culture amplifying its effects. While sustainability resonates with teenagers, it is often overshadowed by price and trend considerations. To foster long-term sustainable consumption, businesses must adopt authentic, creative, and affordable green marketing strategies. Policymakers and educators also have a role in guiding teenagers toward responsible consumer behavior. Aligning teenage consumer psychology with sustainable development goals can create a foundation for future generations to embrace ethical and eco-friendly consumption patterns.

XII. SUGGESTIONS

1. Businesses should integrate sustainability into digital marketing campaigns in authentic and engaging ways.
2. Governments and NGOs should launch awareness campaigns targeting youth, linking consumer choices to sustainable development goals.
3. Schools and colleges should include consumer education in curricula to promote responsible consumption.
4. Influencers and celebrities should be encouraged to promote sustainable lifestyles.
5. Companies should focus on affordability to make sustainable products accessible to teenagers.

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