# Nanotechnology: Emerging Tool in Food Processing, Safety and Quality Enhancement

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**Abstract- Nanotechnology boost the expansion of the food industry, it acts as an innovative domain for the transformation of conventional agriculture and foodstuffs into an entirely novel entity. Nanotechnology comprised of nanoparticles which are classified into four dimensional categories namely, 0D, 1D, 2D and 3D. Nanoparticles are utilized externally in packaging and internally as additives. Nanotechnology aids to prolong the shelf life of the finished product. Nanotechnology strengthens the barrier qualities and also helps in detection of infections and toxins in food products with reference to food safety. Nanotechnology may develop devices for rapid identification of deficiencies of nutrients and the presence of pathogens in food. Numerous applications of nanotechnology in food system and processing have been developed in many countries, some of which include nano-based food additives. Nanotechnology strengthens the functionality and efficiency of frequently used products, by enhancing every aspect of our lives. In spite of its efficiency and eco-friendly qualities, it offers a clean environment by fostering a safer air and water, along with renewable and clean energy for a resilient future.**

**Index-Terms: Nanotechnology, Dimension, Food industry, Nanoparticles**

## I. INTRODUCTION

One of the fascinating domains of science and technology that is attracting extensive research is nanoscience, which holds the potential to substantially boost human existence. Materials with a nanometer or tiny dimension are actually the focus of nanotechnology. Moreover, they comprise harmless, vital elements that maintain their stability under extreme conditions of heat and pressure. These distinctive qualities give potential to boost the taste, texture and other sensory aspects of food (Singh *et al*., 2023). Additionally, nanoparticles can be employed to enhance food protection systems. Due to their ability to possess antimicrobial properties, zinc oxide (ZnO), gold (Au), titanium dioxide ($TiO_2$), silver (Ag) and carbon nanoparticles are manufactured at a rate which is ten times greater than other nanomaterials and find application in food-storing vessels, toothpastes, bandages, air filters, deodorants, paints along with various utility items.

Developed as well as emerging economies are passionate about investing further into this technology as an outcome of the novel economic revolution that has been triggered by nanotechnology. The creation and execution of structures, materials or systems with distinctive characteristics in a wide spectrum of fields, especially agriculture, food and medical, is thereby rendered possible by nanotechnology. A good illustration of a newly developing technology is nanotechnology, which delivers formulated nanomaterials having the enormous potential (Marques *et al*., 2021) to generate products with substantially better performances.

Similar to other industries, the food industry is relying heavily on nanotechnology as a potential technology for resolving issues via creative approaches towards food safety, processing, packaging, and functional foods (Chaudhry *et al*., 2017). It is possible to detect microbial contamination, dangerous chemicals and pesticides in food and other products quickly, sensitively and reliably by using nanosensors and nanopackaging materials (Yu *et al*., 2018). Recent examples include pharmafoods, nutraceuticals, bioactives and functional foods. The food industry utilizes nanoparticles of titanium dioxide, silver, zinc, zinc oxide, silicon dioxide, platinum and gold significantly in a variety of ways.

## II. CLASSIFICATIONS OF NANOMATERIALS

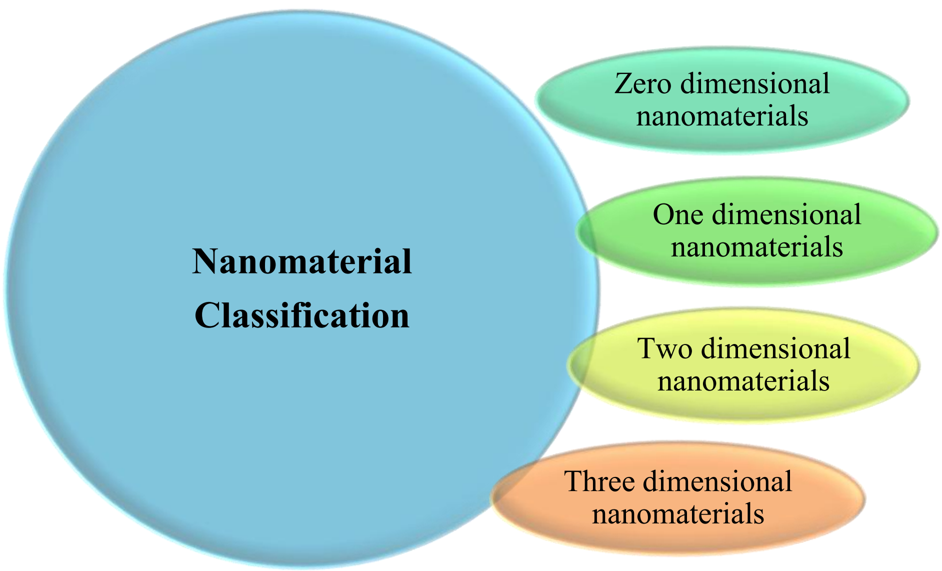
Nanoparticles can be divided into two primary groups, namely organic and inorganic nanoparticles. Carbon nanoparticles and nanotubes are a few instances of organic nanoparticles. On the contrary, inorganic nanoparticles contain semiconductor (zinc oxide and titanium dioxide) nanoparticles, magnetic nanoparticles and nanoparticles of noble metals like gold, silver, and platinum. Inorganic nanoparticles offer multiple benefits over organic nanoparticles primarily because of their suitable applications in catalysis, drug administration, as well as among their optical, chemical, and physical features (Ismail *et al*., 2016). There is a probability that nanoparticles may be formed both intentionally and unintentionally. Nanomaterials that are formed spontaneously or naturally, are proteins, viruses and the nanoparticles formed via volcanic eruptions, are referred to as non-intentional nanomaterials. Nanomaterials that have been intentionally developed are the ones that were subjected to a specific manufacturing procedure. Nanotechnologies are typically described in terms of "intentionally produced Nanomaterials," while "Non-intentionally produced Nanomaterials" typically fall outside the definition (Asmathunisha and Kathiresan, 2013). The unique chemical and physical attributes of nanoparticles, which somewhat differ in contrast to those of their corresponding ions, conduce to certain intriguing properties. The following factors ought to guide the decision-making procedure of nanoparticle materials (Anandharamakrishnan and Parthasarathi, 2019):

- desired nanoparticle dimension

- the stability and solubility which constitute innate characteristics of bioactive substances
- nanoparticles' hydrophobicity and charge on the surface
- capacity of nanomaterials to be biocompatible and biodegradable

Due to the beneficial characteristics, for instance low toxicity and biodegradability, the biopolymer-based nanoparticle delivery techniques have recently drawn an incredible amount of attention.

According to the particle dimensions, size (1-100 nm), shape and chemical composition, nanoparticles are categorized into several groups (Saleh, 2020). From basic components with various dimensionalities, any nanostructure can be constructed. Thus nanomaterials can be categorized into the following groups, depending on the dimension in which the size influence on the resultant property becomes obvious (Mohapatra, 2020):



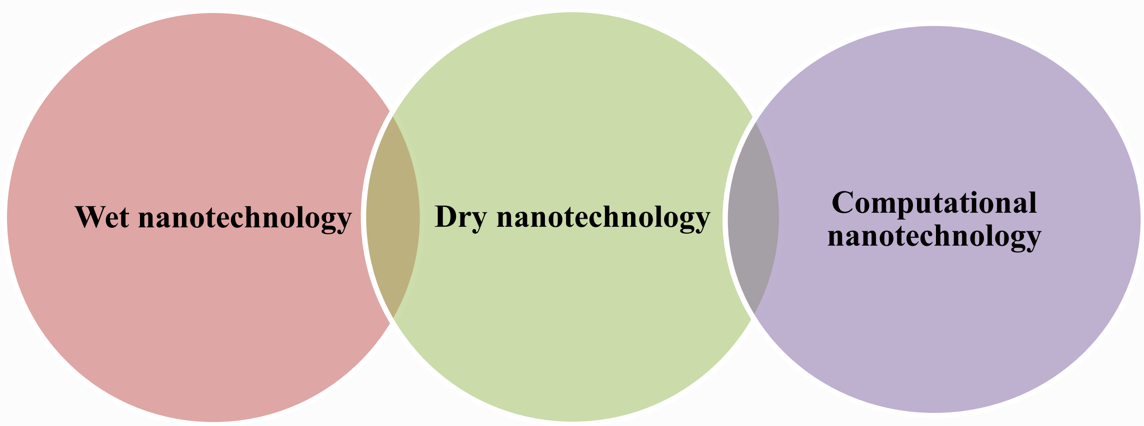

- Zero dimensional nanomaterials (quantum dots): Electron mobility is constrained in all three dimensions in zero-dimensional nanomaterials. No dimension (x, y and z) in this instance is more than 100 nm, all dimensions are at nanoscale level (Wang *et al*., 2020). One illustration of it is fullerance.
- One dimensional nanomaterials (quantum wires): Only the x-direction is available for unfettered electron motion in one-dimensional nanomaterials. In this instance, two dimensions are at nanoscale while the third is not. As a result, nanomaterials with a needle form are produced. It consists of nanowires, nanorods, nanofibres and nanotubes (Lu *et al*., 2009).
- Two dimensional nanomaterials (thin films): The free electrons that exist in two-dimensional nanomaterials (thin films) are able to move freely in the x-y direction. Two of the dimensions are outside the nanoscale, whereas one is at the nanoscale in this instance. Plate-like shapes

can be seen in the 2D nanomaterials. It usually includes nanocoatings, nanolayers and nanofilms (Leonard and Talin, 2011).

- Three dimensional nanomaterials: The free electron can flow in all the three directions (x, y, and z) in three-dimensional nanomaterials, where nanostructured materials are constructed using nanoparticles as foundation units. All the three dimensions exceeding 100 nm exist in these materials. Several arrangements of nanosize crystals with multiple orientations constitute the 3D nanomaterials (Yun *et al*., 2017). It contains multinanolayers (polycrystals) in which the 0D, 1D and 2D structural elements are in intimate contact with one another, such as bundles of nanowires and nanotubes.

## III. TYPES OF NANOTECHNOLOGY

Nanomaterials are substances that can be in the form of a powder or a liquid solution and when it's compared to their micro-sized counterparts, exhibit dramatically unique chemical and physical attributes at the nanoscale. Owing to their features, structure and particle size, nanomaterials can be classified into various categories (Chellaram *et al.,* 2014). The following types of nanotechnology exist:



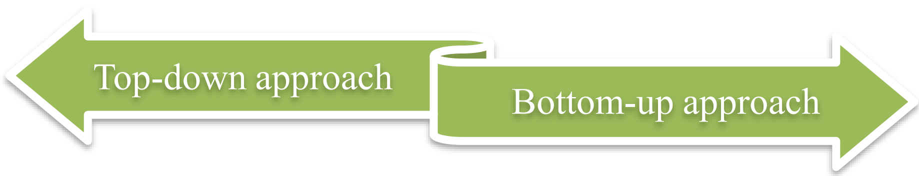

- Wet nanotechnology: Wet nanotechnology depends on living things that reside primarily in aqueous conditions. The functional components that are relevant at the nanoscale level are genetic materials like DNA, enzymes, membranes and other parts of the cell. The achievements of wet nanotechnology can be observed in all living things whose structure, function and form are determined at a nanoscale (Ismail *et al*., 2016).
- Dry nanotechnology: Dry nanotechnology is a byproduct of physical chemistry and surface science, which emphasises on the creation of organic and inorganic nanomaterials including semiconductors and carbon nanotubes, respectively and other metals. It is employed in the production of inorganic materials, metals, semiconductors, silicon, coal and other structures that don't function well in humid environments. Metals and their oxides (semiconductors) are used in dry nanotechnology. These material's active conduction band electrons offer them a unique combination of physical features that make dry nanomaterials promising as magnetic, electrical

and optical devices (Seralathan *et al*., 2014). These electrons also make these materials significantly more reactive to function in a wet environment.

- Computational nanotechnology: Complex nanoscale size materials can be modelled and imitated via computational nanotechnology (Rahuman *et al*., 2022). The crucial development in nanotechnology is the potential of computational nanotechnology to extrapolate and conduct investigations.

## IV. APPROACHES

The production of nanoparticles can be carried out in variety of ways. The food enterprises frequently rely on two nanotechnology approaches.




Through the usage of physical processing methods particularly homogenization, milling, cutting and carving with the goal of reducing the particle size, the top-down strategy is executed. Nano-scale materials generated via top-down technique by the processing of larger items (Ravichandran, 2010). With this method, the size of the object is gradually shrunk. On the contrary, the bottom-up strategy makes effective use of molecules' capacity for self-assembly. By merging tiny, atomic-level components, it may create complex systems. Here, nanomaterial is constructed atom by atom or molecule by molecule using chemical, electrical or physical processes starting with constituents, which are frequently gases or liquids (Arole and Munde, 2014). The self-assembly process involved in "bottom-up" method includes examples such as casein micelles organization and globular proteins folding.

The bottom-up strategy is more widely used than the top-down approach because the surface structure's imperfections constitute the main drawback of the top-down approach (physical methods). Nanostructures and nanomaterials' physical and chemical characteristics would be significantly impacted by the aforementioned flaw (Krishna *et al*., 2022).

| Top down approach | Bottom up approach |
|---|---|
| ➢ Mechanical Milling | ➢ Electro-spinning |
| ➢ Etching | ➢ Sol-gel process |
| ➢ Laser ablation | ➢ Laser pyrolysis |
| ➢ Sputtering | ➢ Chemical vapour deposition |
| ➢ Electro-explosion | ➢ Chemical reduction |

Mechanical milling: A practical method for generating substances at the nanoscale from bulk materials is mechanical milling. The manufacturing of nanocomposites is often aided by mechanical milling, which serves as a useful technique for blending different stages. The target material is being poured into the milling chamber, which contains the carbide balls. A variety of nanocomposite materials, including aluminum/magnesium/copper based nanoalloys, wear-resistant spray coatings and oxide and carbide enhanced aluminium alloys, are created using mechanical milling (El-Eskandarany *et al*., 2021), when constantly used for 100-150 hours. A nanopowder with a size range of 2-20 nm is produced. As a unique kind of nanomaterial, ball-milled carbon nanomaterials have the potential to satisfy needs for energy preservation, energy conversion and restoration of the environment (Baig *et al*., 2021). The potential for ecological remediation, energy preservation as well as the conversion of energy are all provided via innovative class of nanoparticles designated as ball-milled carbon nanomaterials.

Sputtering: The phenomenon involves striking solid surfaces by high-energy particles, especially plasma or gas, with the intent to generate nanomaterials. For creating thin films of nanomaterials, sputtering is thought to be a useful technique. Physical vapour deposition (PVD) processes like sputtering deposit materials on a surface by releasing the atoms from the substance and condensing the discharged atoms onto the surface when a high vacuum environment is maintained. For creating thin films of nanomaterials, sputtering is thought to be a useful technique. When gaseous ions strike a target surface during the sputtering deposition process, depending on the incident gaseous ion energy by which atoms are ejected off the cathode target's surface (Sergievskaya *et al*., 2022). Sputtering is typically carried out in a chamber that has been evacuated and subsequently filled with the sputtering gas. Nanofilms are created by magnetron sputtering on $SiO_2$ and carbon paper substrates. The sputtering approach is intriguing since it is a budget-friendly technique and the composition of the sputtered nanomaterial is similar compared to that of the target material with less foreign matter (Nam *et al*., 2020). Sputtering is a fascinating process however, in contrary to electron-beam lithography, it is more affordable and generates nanomaterials whose composition is identical to the target material and coupled with fewer imperfections.

Laser ablation: Laser ablation synthesis produces nanoparticles by striking the target material with a strong laser beam. The source material or precursor vapourizes during the laser ablation process as an outcome of the high energy laser irradiation, which results in the generation of nanoparticles (Park *et al*., 2017). Vapourized atoms form cloud of plume which later on settles at the substrate surface. Laser ablation is an environmentally friendly method for producing noble metal nanoparticles and this method doesn't require any stabilizing ingredients or chemicals of any sort (Baig *et al*., 2021). The wavelength, fluence and inclusion of laser salt permit tweaking of the nanoparticle metrics, specifically their dimension and distribution. This technique is often used to synthesize a diverse variety of nanomaterials, including metal nanoparticles, carbon nanomaterials, oxide composites and ceramics (Ismail *et al*., 2020).

Electrospinning: The creation of nanostructured materials can be accomplished using one of the most simplistic top-down techniques, electrospinning. It is frequently employed to create nanofibers from a wide range of substances, mostly polymers. Nanofibres are produced from a polymer solution by the voltage-driven fabrication process known as electrospinning, which is controlled by a particular electrohydrodynamic phenomenon. The spinning process starts when a specific voltage is applied to create an electric field between the needle tip and collector (Baig *et al*., 2021). Charges build up at the liquid's surface as the pump keeps the solution flowing at a consistent rate. Soon, the liquid meniscus deforms into a structure known as a Taylor cone due to the stronger electrostatic repulsion than the surface tension at this point. The charged liquid jet shoots out towards the collector as the Taylor cone forms. One electrode, the nozzle, and another electrode, the collector, are linked together and an intense electrical field ranging between 100 to 3000 kV $m^{-1}$ is transmitted across both of electrodes (Chen *et al*., 2018). Typically, in the majority of laboratory systems, the approximate distance between the nozzle and the collector is 5-25 cm. Inorganic, organic, hybrid, hollow polymer, core-shell and other materials have all been developed by adopting this technique.

Sol-Gel Process: The development of various types of premium metal-oxide based nanomaterials uses the Sol-Gel Process extensively. Metal alkoxides are the typical precursors used in the sol-gel process for the synthesis of nanomaterials. During the synthesis of the metal-oxide nanoparticles, the precursor gets switched into a sol, and the sol is subsequently transformed into a network structure that is known as a gel (Danks *et al*., 2016). For this reason, this process is termed as a sol-gel method. There are multiple steps involved in the sol-gel approach for developing nanoparticles. The metal oxide is hydrolyzed in water to create a sol in the initial stage. The solvent viscosity increases due to condensation in the following stage, creating porous structures that subsequently undergo ageing. Metal-hydroxo- or metal-oxo-polymer formation in solution is induced by the creation of hydroxo- (M-OH-M) or oxo- (M-O-M) bridges during the condensation or polycondensation process (Khatri, 2018). Polycondensation continues as a result of ageing, altering the material's structure, characteristics and porosity. Porosity declines with ageing, whereas the spacing between colloidal particles widens. After the ageing process, the gel is dried, and ultimately results in formation of xerogel, aerogel and cryogel. The sol-gel method is cost-effective and has a number of other benefits, particularly the homogeneity of the material generated, the low processing temperature and the technology's ease of use in the production of composites and complicated nanostructures (Parashar *et al*., 2020). The nature of the precursor, the pace of hydrolysis, the amount of time the product is aged, the pH, and the molar ratio of the precursor to water all have a significant effect on the end product developed using the sol-gel process (De Coelho Escobar and Dos Santos, 2014). The uniform quality of the material produced, the low processing temperature, and the technology's ease in synthesizing composites and complicated nanostructures are merely a few of the numerous perks of the sol-gel method, which is also advantageous economically.

## V. APPLICATIONS OF NANOMATERIALS IN FOOD SECTOR

Food is perceived as having a higher quality due to the unique texture, colour, and appearance of nanomaterials. Food nanostructured components and food nanosensing are the two categories of food-related nanotechnology applications. Food nanosensing helps to improve food quality and safety, whereas food nanostructured components include additives which serve as carriers for the intelligent delivery of nutrients & antimicrobial agents, along with food processing and packaging (Gupta *et al.*, 2025).


## VI. CONCLUSION

Over the past few years, the use of nanoscale structures in the food business has surged in popularity. Smaller and more delicate materials are made possible by developments in nanotechnology. Nano-based food additives or preservatives, smart delivery systems, medicine and health care are merely a few of the plenty nanotechnology uses in the food sector and processing techniques that are now prevalent in several nations. The food sectors hold a fairly large potential to incorporate nanotechnology research to benefit society. However, nanotechnology has the potential to revolutionise the manner in which the food is produced and distributed along with simultaneously enhancing its nutritional content. Despite the advancements in food nanotechnology throughout the years, additional research and legislation are still required to alleviate customer concerns and encourage consumer approval of food industry tactics.

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