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Microbial and Botanical Biopesticides: Bioactive Chemistry, Modes of Action and Prospects for Sustainable Crop Protection

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***Abstract*—Heavy dependence on synthetic pesticides has left a familiar set of problems: contaminated soil and water, residues in food, injury to beneficial organisms and increasingly difficult resistance. This review examines microbial and botanical biopesticides as complementary tools rather than as automatic replacements for conventional chemistry. It compares their active principles, modes of action, field uses and practical limitations. Bacillus thuringiensis acts through receptor-mediated disruption of the insect midgut, whereas entomopathogenic fungi such as Beauveria bassiana and Metarhizium anisopliae invade through the cuticle and deploy hydrolytic enzymes and secondary metabolites. Antagonistic and nematophagous fungi add mycoparasitism, antibiosis and induced resistance. Botanical insecticides based on azadirachtin, pyrethrins, rotenoids, nicotine, quassinoids and essential-oil terpenoids provide antifeedant, repellent, neurotoxic, endocrine and respiratory effects. Progress in formulation, microbial consortia, nanotechnology, omics-guided discovery and precision application is gradually improving consistency. The most credible role for biopesticides is within validated, monitoring-based integrated pest management programs that account for selectivity, safety, and persistence and resistance risk.**

***Index Terms*—Biopesticides; botanical insecticides; entomopathogenic fungi; integrated pest management; microbial pesticides; secondary metabolites.**

I. INTRODUCTION

Insect pests, plant pathogens, weeds and plant-parasitic nematodes continue to limit crop production. Synthetic pesticides remain valuable because they act quickly and predictably, but

repeated or poorly targeted use has also produced residues in food and water, injury to pollinators and natural enemies, disruption of agroecosystem processes and widespread resistance [1], [2]. These costs explain the continuing search for crop-protection products that combine efficacy with greater environmental compatibility.

Biopesticides are not a single technology. The term covers living bacterial, fungal, viral and nematode agents; plant preparations containing secondary metabolites; biochemical products such as pheromones; and plant-incorporated protectants expressed by engineered crops [2], [3]. Their biological diversity is important because it supplies multiple points of attack against different pest groups and developmental stages, thereby reducing dependence on any one target site.

Interest in these products has grown steadily over the past two decades [4], [5]. The research emphasis has also changed. Early work often stopped at the discovery of an active organism or crude extract; current studies increasingly ask how the active principle works, whether sublethal effects matter, and whether laboratory performance survives field conditions [6]. For microbial products, formulation quality, shelf life, environmental persistence and farmer acceptance can be as decisive as the intrinsic virulence of the organism [3].

This review brings those strands together. It examines the major microbial and botanical sources of biopesticides, explains their modes of action, and evaluates the formulation, safety, resistance and regulatory issues that determine practical value. Emerging work on nanotechnology, omics, microbial consortia, endophytic delivery and precision agriculture is then considered as a route toward more reliable next-generation products.

II. MICROBIAL BIOPESTICIDES

Bacterial agents

Bacteria include the most commercially established microbial pesticides. The Gram-positive, spore-forming Bacillus thuringiensis (Bt) remains the defining example. During sporulation it produces crystalline δ-endotoxins (Cry proteins) and, in some strains, Cyt proteins; vegetative cells may also secrete Vip proteins [7]–[9]. After susceptible larvae ingest the crystals, the alkaline midgut solubilizes them and host proteases release the active toxin. Binding to midgut receptors is followed by membrane insertion, pore formation, osmotic imbalance, cell lysis and death [10]. This receptor-dependent sequence accounts for the narrow host range and favorable vertebrate safety profile of many Bt products [11].

The Bt repertoire is broader than the classical Cry family. Vip3A and related vegetative insecticidal proteins act against lepidopteran pests whose susceptibility to Cry toxins may be limited, while secreted insecticidal proteins add further breadth [12], [13]. That molecular variety is now being used deliberately: toxin pyramids, rotations and mixtures with distinct receptors or target sites are central to resistance-management strategies for both sprays and Bt crops [14], [15].

Other bacteria fill distinct niches. Lysinibacillus sphaericus produces binary and other mosquitocidal toxins for larval control in aquatic habitats [16]. Bacillus subtilis and B. amyloliquefaciens suppress plant pathogens through surfactins, iturins, fengycins, hydrolytic

enzymes and induced systemic resistance [17], [18]. Fluorescent pseudomonads combine antibiotics, siderophores and competition for nutrients or infection sites [19]. Engineered spore-surface display of heterologous enzymes illustrates how bacterial platforms are being redesigned for greater stability and functional persistence [20].

Fungal agents

Entomopathogenic fungi differ from gut-active bacterial toxins because they infect directly through the insect cuticle. They are therefore useful against sucking pests that may never ingest a treated surface [21], [22]. Infection proceeds through conidial adhesion, germination, enzymatic and mechanical penetration, proliferation in the hemocoel and, finally, host death and external sporulation. Temperature, humidity, ultraviolet exposure, substrate pH and host susceptibility can each shift the outcome [23].

Beauveria bassiana is the most extensively developed mycoinsecticide. Its virulence depends on cuticle-degrading proteases, chitinases and lipases, together with metabolites such as beauvericin, bassianolide, bassianin, tenellin and oosporein [24], [25]. The fungus can also colonize plants endophytically without causing disease. In that setting it may prime plant defenses, improve growth and reduce later herbivore performance, creating a useful bridge between plant protection and pest suppression [26], [27].

Metarhizium anisopliae has been formulated against soil- and foliage-dwelling pests, although performance remains sensitive to temperature, moisture, solar exposure and formulation quality [26]. Isaria fumosorosea is used mainly against whiteflies, aphids and thrips, while Lecanicillium lecanii is associated with aphids, whiteflies and scale insects; both require sufficiently humid conditions for reliable germination and infection [22].

Antagonistic fungi extend microbial control beyond insects. Trichoderma harzianum, T. virens and T. asperellum suppress pathogens through mycoparasitism, nutrient and space competition, antibiosis, cell-wall-degrading enzymes and induced resistance, often while promoting plant growth [28]. Among nematophagous fungi, Purpureocillium lilacinum attacks several nematode stages, whereas Pochonia chlamydosporia is especially associated with eggs of root-knot and cyst nematodes [26].

TABLE 1. REPRESENTATIVE MICROBIAL BIOPESTICIDES, TARGET ORGANISMS AND PRINCIPAL MODES OF ACTION

Agent	Target organisms	Key bioactive factors	Principal mode of action
Bacillus thuringiensis	Lepidopteran, coleopteran and dipteran larvae	Cry, Cyt and Vip proteins	Midgut solubilization and activation; receptor binding, pore formation and cell lysis
Lysinibacillus sphaericus	Mosquito larvae	Binary (Bin) toxin	Midgut epithelial binding and cellular lysis

Agent	Target organisms	Key bioactive factors	Principal mode of action
Bacillus subtilis / B. amyloliquefaciens	Fungal and bacterial plant pathogens	Surfactins, iturins and fengycins	Membrane disruption, antibiosis and induced systemic resistance
Pseudomonas fluorescens	Soil-borne plant pathogens	Antibiotics, siderophores and hydrolytic enzymes	Antibiosis, niche competition and induced resistance
Beauveria bassiana	Broad insect host range	Cuticle-degrading proteases and chitinases; beauvericin, bassianolide and tenellin	Cuticular adhesion and penetration, hemocoel proliferation and toxin-mediated death
Metarhizium anisopliae	Wide range of insect pests	Cuticle-degrading enzymes and destruxins	Contact infection and internal colonization
Isaria fumosorosea	Whiteflies, aphids and thrips	Hydrolytic enzymes and metabolites	Cuticular infection and mycosis
Lecanicillium lecanii	Aphids, whiteflies and scale insects	Enzymes and antimicrobial metabolites	Cuticular infection and antibiosis
Trichoderma spp.	Fungal plant pathogens	Cell-wall-degrading enzymes, peptaibols and volatiles	Mycoparasitism, competition, antibiosis and induced resistance
Purpureocillium lilacinum	Plant-parasitic nematodes	Proteases, chitinases and toxic metabolites	Nematode parasitism and population suppression
Pochonia chlamydosporia	Root-knot and cyst nematode eggs	Enzymes and metabolites	Egg parasitism and hatching interference

Viruses, nematodes and plant-incorporated protectants

Baculoviruses, especially nucleopolyhedroviruses, offer highly specific control of lepidopteran pests. Occlusion bodies dissolve after ingestion, initiate systemic infection and usually kill the host within days, releasing progeny virus into the pest population [29]. Entomopathogenic nematodes in the Steinernematidae and Heterorhabditidae carry Xenorhabdus and Photorhabdus bacteria into the insect hemocoel; their active host-searching behavior makes them valuable against soil-dwelling and otherwise concealed pests [3], [29]. Plant-incorporated protectants such as Bt maize and cotton

provide continuous tissue-level expression of Cry proteins, but their durability depends on disciplined insect-resistance management [11], [15].

III. BOTANICAL BIOPESTICIDES

Plants have evolved a broad chemical defense system that includes terpenoids, limonoids, alkaloids, phenolics, flavonoids, saponins, tannins, coumarins and sulfur-containing metabolites [30], [31]. Products derived from this chemistry can deter feeding, repel adults, disrupt development, poison nervous systems or inhibit microorganisms. Rapid environmental degradation is often an advantage where residues are restricted, although it also shortens residual control.

Neem (Azadirachta indica) remains the best-studied botanical source. Its principal limonoid, azadirachtin, interferes with feeding, molting, metamorphosis, reproduction and development rather than producing immediate neurotoxic knockdown; salannin, nimbin and meliantriol contribute complementary activity [32], [33]. Azadirachtin disrupts endocrine control involving ecdysteroids and juvenile hormone, leading to failed molts, developmental arrest and reduced fecundity. Because seed chemistry varies with provenance, season and extraction method, controlled bioreactor production has been investigated as a standardization strategy [34].

Pyrethrum flowers from Tanacetum cinerariifolium contain six insecticidal esters. These pyrethrins prolong the open state of voltage-gated sodium channels and produce rapid knockdown [35], [36]. Other historically important botanicals include rotenoids from Derris roots, which inhibit mitochondrial electron transport; karanjin and pongamol from Pongamia pinnata; nicotine from Nicotiana tabacum, an agonist of insect nicotinic acetylcholine receptors; and quassinoids from Quassia amara, which are powerful antifeedants [30], [31], [37].

Essential oils supply another major group. Limonene, linalool, geraniol, citral and eugenol can act as contact toxins, fumigants, repellents or antimicrobial agents [38], [39]. Important sources include Ocimum, Citrus, Thymus, Origanum and Cymbopogon, while citrus-peel waste offers a route to link pest management with by-product valorization. Sulfur-containing plant chemistry is also relevant: allicin released from disrupted garlic tissues has broad antimicrobial, insecticidal and nematicidal activity, and glucosinolates in Brassicaceae yield biofumigant isothiocyanates after hydrolysis [40], [41]. Plant-derived fumigants have particular value in stored-product protection [42].

TABLE 2. SELECTED PLANT SPECIES EXPLOITED AS SOURCES OF BIOPESTICIDES

Plant species	Plant part used	Major bioactive constituent(s)	Principal activity
Azadirachta indica (Meliaceae)	Seeds and leaves	Azadirachtin, salannin, nimbin and meliantriol	Antifeedant activity, growth regulation, repellency and oviposition deterrence

Plant species	Plant part used	Major bioactive constituent(s)	Principal activity
Tanacetum cinerariifolium (Asteraceae)	Flowers	Pyrethrins I and II, cinerins and jasmolins	Rapid knockdown through sodium-channel modulation
Derris spp. (Fabaceae)	Roots	Rotenone and other rotenoids	Inhibition of mitochondrial electron transport
Pongamia pinnata (Fabaceae)	Seeds	Karanjin and pongamol	Insecticidal, antifeedant and growth-regulating activity
Nicotiana tabacum (Solanaceae)	Leaves	Nicotine	Agonism of nicotinic acetylcholine receptors
Quassia amara (Simaroubaceae)	Wood	Quassin and neoquassin	Potent antifeedant and insecticidal activity
Ocimum spp. (Lamiaceae)	Leaves and aerial parts	Eugenol, linalool and methyl eugenol	Repellent, fumigant and contact insecticidal activity
Citrus spp. (Rutaceae)	Peel	Limonene and other monoterpenes	Fumigant, repellent and contact toxicity
Allium sativum (Amaryllidaceae)	Bulbs	Allicin and related thiosulfinates	Antimicrobial, insecticidal and nematicidal activity
Brassica spp. (Brassicaceae)	Seeds and tissues	Glucosinolates, which release isothiocyanates on hydrolysis	Biofumigant, nematicidal and antimicrobial activity

IV. PHYTOCHEMICAL CLASSES AND THEIR MODES OF ACTION

Terpenoids form the largest class of plant specialized metabolites and include insecticides, antifeedants, repellents and fumigants. Linalool, limonene, thymol, carvacrol and 1,8-cineole can inhibit acetylcholinesterase, alter GABA-gated chloride channels or octopaminergic signaling, and disturb neuronal ion balance and mitochondrial respiration [43], [44]. Their volatility makes them effective in enclosed storage systems, but field use requires formulations that slow evaporation.

Alkaloids such as nicotine and anabasine overstimulate nicotinic acetylcholine receptors, producing hyperexcitation, paralysis and death; their mammalian toxicity is a reminder that natural origin does not equal low risk [30], [37]. Flavonoids, including quercetin, rutin, kaempferol and naringenin, can inhibit digestive enzymes, reduce nutrient use and alter oviposition, with structure–activity relationships strongly affected by hydroxylation and glycosylation [45]. Saponins bind membrane

sterols and increase permeability [46], while tannins bind dietary and digestive proteins and thereby suppress growth and fecundity [47].

Activity in botanical preparations rarely rests on one molecule alone. Crude extracts and essential oils contain mixtures whose constituents may act additively, synergistically or antagonistically, and minor components can materially change the performance of a dominant compound [30], [48]. Chemical profiling is therefore a prerequisite for reproducible products. Across the documented phytochemical classes, mechanisms include receptor agonism, ion-channel and acetylcholinesterase disruption, endocrine interference, feeding deterrence, digestive and respiratory inhibition, membrane and mitochondrial damage, oxidative stress and reproductive impairment [38], [39]. This diversity provides useful rotation and mixture options for resistance management.

TABLE 3. MAJOR PHYTOCHEMICAL CLASSES IMPLICATED IN BIOPESTICIDAL ACTIVITY

Class	Representative compounds	Documented effects	Proposed mechanism(s)
Monoterpenes	Limonene, linalool, geraniol, citral, α-pinene and 1,8-cineole	Insecticidal, repellent, fumigant and acaricidal	Acetylcholinesterase inhibition; GABAergic and octopaminergic modulation; ion-channel disturbance
Phenolic monoterpenes	Thymol and carvacrol	Insecticidal, antimicrobial and antifungal	Neurotoxicity and membrane disruption
Phenylpropanoids	Eugenol	Insecticidal and antimicrobial	Neurotoxicity and membrane perturbation
Limonoids	Azadirachtin, salannin and nimbin	Antifeedant, growth-disrupting and reproductive effects	Interference with ecdysteroid and juvenile-hormone pathways
Alkaloids	Nicotine and anabasine	Neurotoxicity and paralysis	Agonism of nicotinic acetylcholine receptors
Flavonoids	Quercetin, rutin, kaempferol and naringenin	Antifeedant, growth and oviposition inhibition	Digestive-enzyme inhibition and altered nutrient utilization
Saponins	Triterpenoid and steroidal glycosides	Insecticidal and antimicrobial	Membrane-sterol binding and permeability changes
Tannins	Hydrolyzable and condensed tannins	Feeding deterrence and antinutritional effects	Protein binding and digestive-enzyme inhibition
Coumarins	Coumarin and derivatives	Insecticidal and antifungal	Developmental and enzymatic interference

Class	Representative compounds	Documented effects	Proposed mechanism(s)
Pyrethrins	Pyrethrins I–II, cinerins and jasmolins	Rapid knockdown and mortality	Prolonged opening of voltage-gated sodium channels
Sulfur compounds	Allicin and isothiocyanates	Insecticidal, nematicidal and antimicrobial	Thiol-reactive protein and enzyme inhibition
Steroidal glycoalkaloids	α-Solanine and α-tomatine	Antifeedant and toxic effects	Membrane disruption and digestive inhibition

V. APPLICATIONS ACROSS CROPPING SYSTEMS

Bt sprays and Bt-expressing cultivars remain the principal biopesticide technologies for lepidopteran control in field crops. Metarhizium-based products are used against soil pests and locusts, while Trichoderma seed and soil treatments suppress root diseases in cereals, oilseeds and pulses [28], [29]. Protected horticulture is an especially suitable niche because greenhouse humidity favors Beauveria bassiana, Isaria fumosorosea and Lecanicillium lecanii against whiteflies, aphids and thrips [26].

In perennial and high-value crops, nematophagous fungi and entomopathogenic nematodes provide options where conventional nematicides or soil insecticides have been withdrawn [26]. Stored-product protection remains a strong application for essential oils, pyrethrum powders and plant-derived fumigants because the volatility that limits outdoor persistence becomes an advantage in enclosed grain systems [42]. Organic and residue-sensitive export markets provide additional demand, and Bacillus-based larvicides continue to serve public-health mosquito control [16]. Endophytic entomopathogens extend the model further by providing prophylactic protection within plant tissues [27].

VI. FORMULATION AND DELIVERY TECHNOLOGIES

The distance between laboratory activity and dependable field control is often a formulation problem. Microbial products are supplied as dusts, wettable powders, granules, aqueous suspensions, oil dispersions and emulsifiable concentrates. Each format must protect the organism from desiccation, ultraviolet radiation and temperature extremes while maintaining shelf life, uniform coverage and compatibility with farm equipment [3], [26]. Seed dressings remain an economical route for soil-applied agents because the active ingredient can be fixed to the seed coat with suitable carriers and warning pigments [49].

Botanical products face a parallel problem at the chemical level. Essential oils volatilize, oxidize and photodegrade, and their composition changes with genotype, geography, season, plant age and extraction method [39]. Marker-compound quantification, controlled cultivation and bioreactor production can reduce batch variability [34]. Timing is equally important: fungal products generally

require adequate humidity and are often best applied early or late in the day, whereas short-lived botanical sprays may require repetition. Monitoring-based thresholds within IPM programs make these narrower performance windows manageable [1], [2].

VII. SAFETY, RESISTANCE AND REGULATION

Biopesticides should not be treated as intrinsically harmless. Bt Cry toxins have favorable mammalian toxicology because activation depends on insect midgut conditions and specific receptors that vertebrates lack [11]. Safety assessments of Beauveria products also indicate low risk to people and most non-target organisms when label directions are followed [21]. By contrast, nicotine and rotenone can be highly toxic to mammals and aquatic organisms, and their use has been restricted accordingly [30]. Product-specific testing for beneficial insects, soil fauna and aquatic organisms remains essential.

Resistance is a second shared constraint. Field-evolved resistance to Bt toxins shows that biological products can impose strong selection pressure; pyramids, refuges, rotation and integration with unrelated tactics are needed to preserve susceptibility [14], [15]. Phytochemical mixtures may slow resistance when their components are selected on mechanistic grounds rather than blended empirically. Regulatory requirements differ among jurisdictions, and efficacy, toxicology and environmental-fate data still account for a substantial part of development cost even where biopesticide pathways are shorter than those for synthetic pesticides [1], [2], [50].

VIII. EMERGING DIRECTIONS

Several technologies are converging on the weaknesses that have limited biopesticide adoption. Genomics, transcriptomics and metabolomics are accelerating the discovery of virulence genes, secondary-metabolite clusters and bioactive plant compounds, allowing mechanism-guided screening instead of mortality assays alone [6], [25]. Nanoemulsions, lipid nanoparticles and polymer matrices can protect essential oils from volatilization and photodegradation, provide controlled release and improve leaf adhesion. Consortia that pair complementary organisms—such as Trichoderma with Bacillus, or mycorrhizal fungi with entomopathogens—are being designed to suppress several pest groups while supporting plant growth [3], [28].

Endophytic delivery allows entomopathogenic fungi to colonize plant tissues and reduce dependence on repeated foliar sprays [27]. Precision-agriculture tools can then match application to pest phenology and to microclimatic windows of temperature and humidity. Synthetic-biology and fermentation approaches, including spore-surface display and in situ cultivation of toxin-producing cells, point toward more scalable and quality-controlled manufacture [20], [34].

IX. CONCLUSION

Biopesticides have moved from peripheral alternatives to credible components of sustainable crop protection. Microbial agents provide receptor-specific gut toxins, contact infection,

mycoparasitism, antibiosis and induced resistance. Botanicals contribute chemically diverse products that act on insect nervous, endocrine, digestive, respiratory and reproductive systems. Used together within IPM, these tools reduce dependence on single-site synthetic chemistry and create more options for resistance management.

The next phase should be judged by field reliability rather than by discovery volume alone. Priorities include rigorous identification of active principles, formulations that protect biological and chemical activity, standardized production, transparent non-target and mammalian safety assessment, resistance monitoring and validation under commercial farming conditions. Biopesticides are therefore best viewed not as one-for-one substitutes for synthetic pesticides but as essential parts of diversified, ecologically informed crop-protection systems [1], [2], [5].

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REFERENCES

[1]. D. Chandler, A. S. Bailey, G. M. Tatchell, G. Davidson, J. Greaves, and W. P. Grant, “The development, regulation and use of biopesticides for integrated pest management,” Philosophical Transactions of the Royal Society B: Biological Sciences, vol. 366, no. 1573, pp. 1987–1998, 2011, doi: 10.1098/rstb.2010.0390.

[2]. T. Glare et al., “Have biopesticides come of age?” Trends in Biotechnology, vol. 30, no. 5, pp. 250–258, 2012, doi: 10.1016/j.tibtech.2012.01.003.

[3]. K. Tadesse Mawcha, L. Malinga, D. Muir, J. Ge, and D. Ndolo, “Recent advances in biopesticide research and development with a focus on microbials,” F1000Research, vol. 13, Art. no. 1071, 2024, doi: 10.12688/f1000research.154392.2.

[4]. Y. Thakore, “The biopesticide market for global agricultural use,” Industrial Biotechnology, vol. 2, no. 3, pp. 194–208, 2006, doi: 10.1089/ind.2006.2.194.

[5]. M. B. Isman, “Botanical insecticides in the twenty-first century—Fulfilling their promise?” Annual Review of Entomology, vol. 65, pp. 233–249, 2020, doi: 10.1146/annurev-ento-011019-025010.

[6]. L. J. Collares, L. M. Turchen, and R. N. C. Guedes, "Research trends, biases, and gaps in phytochemicals as insecticides: Literature survey and meta-analysis," Plants, vol. 12, no. 2, Art. no. 318, 2023, doi: 10.3390/plants12020318.

[7]. S. S. Gill, E. A. Cowles, and P. V. Pietrantonio, "The mode of action of Bacillus thuringiensis endotoxins," Annual Review of Entomology, vol. 37, pp. 615–634, 1992, doi: 10.1146/annurev.en.37.010192.003151.

[8]. E. Schnepf et al., "Bacillus thuringiensis and its pesticidal crystal proteins," Microbiology and Molecular Biology Reviews, vol. 62, no. 3, pp. 775–806, 1998, doi: 10.1128/MMBR.62.3.775-806.1998.

[9]. L. Palma, D. Muñoz, C. Berry, J. Murillo, and P. Caballero, "Bacillus thuringiensis toxins: An overview of their biocidal activity," Toxins, vol. 6, no. 12, pp. 3296–3325, 2014, doi: 10.3390/toxins6123296.

[10]. A. Bravo, S. S. Gill, and M. Soberón, "Mode of action of Bacillus thuringiensis Cry and Cyt toxins and their potential for insect control," Toxicon, vol. 49, no. 4, pp. 423–435, 2007, doi: 10.1016/j.toxicon.2006.11.022.

[11]. J. P. Siegel, "The mammalian safety of Bacillus thuringiensis-based insecticides," Journal of Invertebrate Pathology, vol. 77, no. 1, pp. 13–21, 2001, doi: 10.1006/jipa.2000.5000.

[12]. J. J. Estruch, G. W. Warren, M. A. Mullins, G. J. Nye, J. A. Craig, and M. G. Koziel, "Vip3A, a novel Bacillus thuringiensis vegetative insecticidal protein with a wide spectrum of activities against lepidopteran insects," Proceedings of the National Academy of Sciences, vol. 93, no. 11, pp. 5389–5394, 1996, doi: 10.1073/pnas.93.11.5389.

[13]. M. Chakroun, N. Banyuls, Y. Bel, B. Escriche, and J. Ferré, "Bacterial vegetative insecticidal proteins (Vip) from entomopathogenic bacteria," Microbiology and Molecular Biology Reviews, vol. 80, no. 2, pp. 329–350, 2016, doi: 10.1128/MMBR.00060-15.

[14]. B. E. Tabashnik, T. Brévault, and Y. Carrière, "Insect resistance to Bt crops: Lessons from the first billion acres," Nature Biotechnology, vol. 31, no. 6, pp. 510–521, 2013, doi: 10.1038/nbt.2597.

[15]. Y. Carrière, J. A. Fabrick, and B. E. Tabashnik, "Can pyramids and seed mixtures delay resistance to Bt crops?" Trends in Biotechnology, vol. 34, no. 4, pp. 291–302, 2016, doi: 10.1016/j.tibtech.2015.12.011.

[16]. C. Berry, "The bacterium, Lysinibacillus sphaericus, as an insect pathogen," Journal of Invertebrate Pathology, vol. 109, no. 1, pp. 1–10, 2012, doi: 10.1016/j.jip.2011.11.008.

[17]. M. Ongena and P. Jacques, "Bacillus lipopeptides: Versatile weapons for plant disease biocontrol," Trends in Microbiology, vol. 16, no. 3, pp. 115–125, 2008, doi: 10.1016/j.tim.2007.12.009.

[18]. A. Hashem, B. Tabassum, and E. F. Abd-Allah, "Bacillus subtilis: A plant-growth promoting rhizobacterium that also impacts biotic stress," Saudi Journal of Biological Sciences, vol. 26, no. 6, pp. 1291–1297, 2019, doi: 10.1016/j.sjbs.2019.05.004.

[19]. D. Haas and G. Défago, "Biological control of soil-borne pathogens by fluorescent pseudomonads," Nature Reviews Microbiology, vol. 3, no. 4, pp. 307–319, 2005, doi: 10.1038/nrmicro1129.

[20]. A. Rostami, K. Hinc, F. Goshadrou, A. Shali, and M. Bayat, "Display of B. pumilus chitinase on the surface of B. subtilis spore as a potential biopesticide," Pesticide Biochemistry and Physiology, vol. 140, pp. 17–23, 2017, doi: 10.1016/j.pestbp.2017.05.008.

[21]. G. Zimmermann, "Review on safety of the entomopathogenic fungi Beauveria bassiana and Beauveria brongniartii," Biocontrol Science and Technology, vol. 17, no. 6, pp. 553–596, 2007, doi: 10.1080/09583150701309006.

[22]. A. Litwin, M. Nowak, and S. Różalska, "Entomopathogenic fungi: Unconventional applications," Reviews in Environmental Science and Bio/Technology, vol. 19, pp. 23–42, 2020, doi: 10.1007/s11157-020-09525-1.

[23]. J. Padmavathi, K. U. Devi, and C. U. M. Rao, "The optimum and tolerance pH range is correlated to colonial morphology in isolates of the entomopathogenic fungus Beauveria bassiana—A potential biopesticide," World Journal of Microbiology and Biotechnology, vol. 19, pp. 469–477, 2003, doi: 10.1023/A:1025151000398.

[24]. M. G. Feng, T. J. Poprawski, and G. G. Khachatourians, "Production, formulation and application of the entomopathogenic fungus Beauveria bassiana for insect control: Current status," Biocontrol Science and Technology, vol. 4, no. 1, pp. 3–34, 1994, doi: 10.1080/09583159409355309.

[25]. L. Zhang, O. E. Fasoyin, I. Molnár, and Y. Xu, "Secondary metabolites from hypocrealean entomopathogenic fungi: Novel bioactive compounds," Natural Product Reports, vol. 37, no. 9, pp. 1181–1206, 2020, doi: 10.1039/C9NP00065H.

[26]. G. M. Mascarin and S. T. Jaronski, "The production and uses of Beauveria bassiana as a microbial insecticide," World Journal of Microbiology and Biotechnology, vol. 32, Art. no. 177, 2016, doi: 10.1007/s11274-016-2131-3.

[27]. F. E. Vega, "The use of fungal entomopathogens as endophytes in biological control: A review," Mycologia, vol. 110, no. 1, pp. 4–30, 2018, doi: 10.1080/00275514.2017.1418578.

[28]. R. Mukhopadhyay and D. Kumar, "Trichoderma: A beneficial antifungal agent and insights into its mechanism of biocontrol potential," Egyptian Journal of Biological Pest Control, vol. 30, Art. no. 133, 2020, doi: 10.1186/s41938-020-00333-x.

[29]. L. A. Lacey, D. Grzywacz, D. I. Shapiro-Ilan, R. Frutos, M. Brownbridge, and M. S. Goettel, "Insect pathogens as biological control agents: Back to the future," Journal of Invertebrate Pathology, vol. 132, pp. 1–41, 2015, doi: 10.1016/j.jip.2015.07.009.

[30]. M. B. Isman, "Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world," Annual Review of Entomology, vol. 51, pp. 45–66, 2006, doi: 10.1146/annurev.ento.51.110104.151146.

[31]. R. Pavela, "History, presence and perspective of using plant extracts as commercial botanical insecticides and farm products for protection against insects—A review," Plant Protection Science, vol. 52, no. 4, pp. 229–241, 2016, doi: 10.17221/31/2016-PPS.

[32]. A. J. Mordue (Luntz) and A. Blackwell, "Azadirachtin: An update," Journal of Insect Physiology, vol. 39, no. 11, pp. 903–924, 1993, doi: 10.1016/0022-1910(93)90001-8.

[33]. A. J. Mordue (Luntz) and A. J. Nisbet, "Azadirachtin from the neem tree Azadirachta indica: Its action against insects," Anais da Sociedade Entomológica do Brasil, vol. 29, no. 4, pp. 615–632, 2000, doi: 10.1590/S0301-80592000000400001.

[34]. G. Prakash and A. K. Srivastava, "Production of biopesticides in an in situ cell retention bioreactor," Applied Biochemistry and Biotechnology, vol. 151, pp. 307–318, 2008, doi: 10.1007/s12010-008-8191-6.

[35]. J. E. Casida, "Pyrethrum flowers and pyrethroid insecticides," Environmental Health Perspectives, vol. 34, pp. 189–202, 1980, doi: 10.1289/ehp.8034189.

[36]. D. M. Soderlund and J. R. Bloomquist, "Neurotoxic actions of pyrethroid insecticides," Annual Review of Entomology, vol. 34, pp. 77–96, 1989, doi: 10.1146/annurev.en.34.010189.000453.

[37]. M. Tomizawa and J. E. Casida, "Neonicotinoid insecticide toxicology: Mechanisms of selective action," Annual Review of Pharmacology and Toxicology, vol. 45, pp. 247–268, 2005, doi: 10.1146/annurev.pharmtox.45.120403.095930.

[38]. C. Regnault-Roger, C. Vincent, and J. T. Arnason, "Essential oils in insect control: Low-risk products in a high-stakes world," Annual Review of Entomology, vol. 57, pp. 405–424, 2012, doi: 10.1146/annurev-ento-120710-100554.

[39]. R. Pavela and G. Benelli, "Essential oils as ecofriendly biopesticides? Challenges and constraints," Trends in Plant Science, vol. 21, no. 12, pp. 1000–1007, 2016, doi: 10.1016/j.tplants.2016.10.005.

[40]. J. Borlinghaus, F. Albrecht, M. C. H. Gruhlke, I. D. Nwachukwu, and A. J. Slusarenko, "Allicin: Chemistry and biological properties," Molecules, vol. 19, no. 8, pp. 12591–12618, 2014, doi: 10.3390/molecules190812591.

[41]. B. A. Halkier and J. Gershenzon, "Biology and biochemistry of glucosinolates," Annual Review of Plant Biology, vol. 57, pp. 303–333, 2006, doi: 10.1146/annurev.arplant.57.032905.105228.

[42]. S. Rajendran and V. Sriranjini, "Plant products as fumigants for stored-product insect control," Journal of Stored Products Research, vol. 44, no. 2, pp. 126–135, 2008, doi: 10.1016/j.jspr.2007.08.003.

[43]. E. Enan, "Insecticidal activity of essential oils: Octopaminergic sites of action," Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, vol. 130, no. 3, pp. 325–337, 2001, doi: 10.1016/S1532-0456(01)00255-1.

[44]. M. E. Maffei, J. Gertsch, and G. Appendino, "Plant volatiles: Production, function and pharmacology," Natural Product Reports, vol. 28, no. 8, pp. 1359–1380, 2011, doi: 10.1039/C1NP00021G.

[45]. M. S. J. Simmonds, "Flavonoid–insect interactions: Recent advances in our knowledge," Phytochemistry, vol. 64, no. 1, pp. 21–30, 2003, doi: 10.1016/S0031-9422(03)00293-0.

[46]. E. De Geyter, L. Swevers, S. Caccia, D. Geelen, and G. Smagghe, "Saponins show high entomotoxicity by cell membrane permeation in Lepidoptera," Pest Management Science, vol. 68, no. 8, pp. 1199–1205, 2012, doi: 10.1002/ps.3284.

[47]. R. V. Barbehenn and C. P. Constabel, "Tannins in plant–herbivore interactions," Phytochemistry, vol. 72, no. 13, pp. 1551–1565, 2011, doi: 10.1016/j.phytochem.2011.01.040.

[48]. R. Pavela, "Acute toxicity and synergistic and antagonistic effects of the aromatic compounds of some essential oils against Culex quinquefasciatus Say larvae," Parasitology Research, vol. 114, pp. 3835–3853, 2015, doi: 10.1007/s00436-015-4614-9.

[49]. T. S. Woods, "Pesticide formulations," in Encyclopedia of Agrochemicals. Hoboken, NJ, USA: Wiley, 2002, doi: 10.1002/047126363X.agr185.

[50]. P. Leng, "Applications and development trends in biopesticides," African Journal of Biotechnology, vol. 10, no. 86, pp. 19864–19873, 2011, doi: 10.5897/AJBX11.009.