Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 01 (JAN-FEB, 2026)
Available online at http://www.agriarticles.com
©Agri Articles, ISSN: 2582-9882

Biopesticides: An Eco-Friendly Approach to Plant Protection

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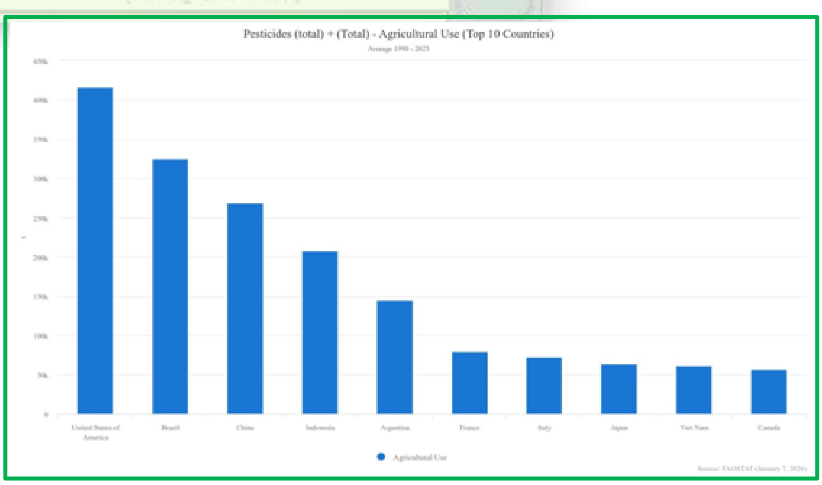
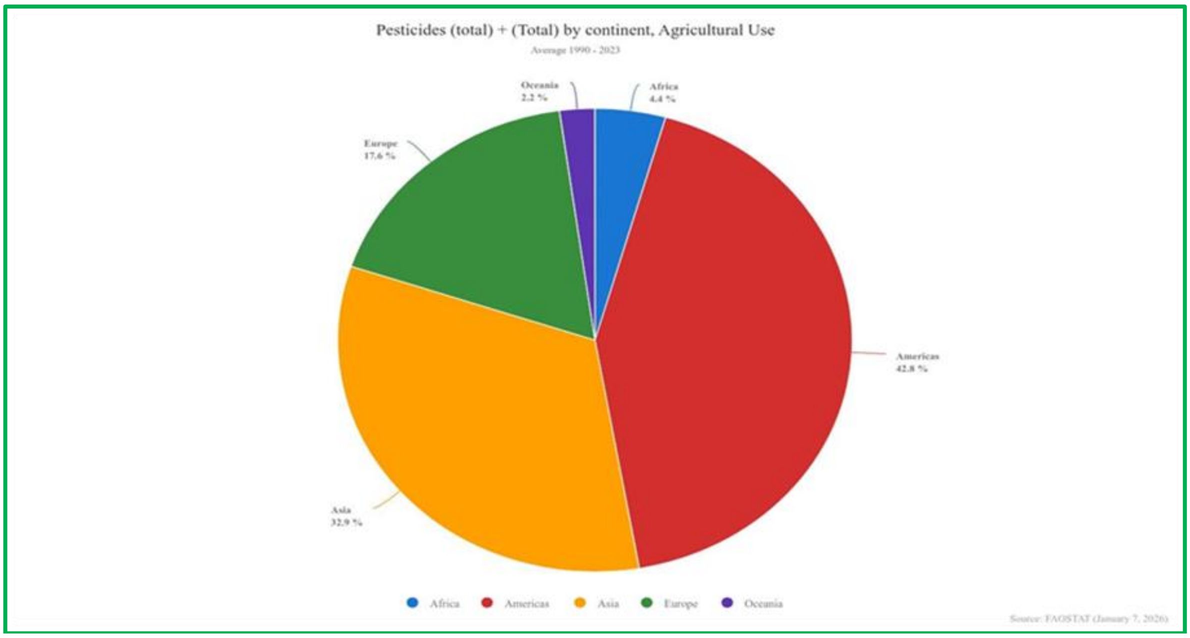
The world's population is increasing at a rapid pace and is expected to reach nearly 9.7 billion by the year 2050, with the majority of this growth occurring in Africa and Asia. This rapid expansion has placed immense pressure on agriculture and allied sectors to ensure adequate food production, thereby increasing the demand for agricultural inputs. To address these challenges and meet future food requirements, it is essential to enhance both the productivity and sustainability of agricultural systems through innovative and improved approaches. Agricultural output can be improved by increasing crop yields using organic inputs such as manures and bio based treatments, including biopesticides, as well as by minimizing yield losses caused by biotic and abiotic stresses. Biopesticides, derived from natural sources or living microorganisms, represent a promising alternative for pest management as they help reduce crop losses while maintaining product quality.

In contrast, the widespread use of chemical pesticides to control pests and diseases in agricultural fields has raised serious environmental and health concerns. These synthetic chemicals are associated with long-term adverse effects, including carcinogenic risks and developmental abnormalities, and they persist in the environment due to their non-biodegradable nature. Despite their strong pest-control efficacy and widespread commercial availability, chemical pesticides adversely affect soil health, often leading to nutrient depletion and increased susceptibility of crops to diseases. Such outcomes are detrimental to sustainable soil management and pose a threat to long-term food and nutritional security.

According to the Food and Agriculture Organization of the United Nations (FAO, 2025), the United States, Brazil and China, are the largest consumers of pesticides worldwide. Among Indian states, Uttar Pradesh recorded the highest pesticide consumption, followed by Jammu and Kashmir. Irrespective of that in India, data from the Ministry of Chemicals and Fertilizers (2024–2025) indicate that the consumption of chemical pesticides has decreased from 68926.18 metric tons in 2020–2021 to 67221.22 metric tons in 2024–2025. These figures highlight the urgent need to explore and promote alternative pest management strategies, particularly the increased adoption of biopesticides.



Biopesticides are natural pest-control agents derived from plants, animals, and microorganisms such as bacteria, cyanobacteria, and microalgae. They function through bioactive compounds, genes, or metabolites that help suppress pests and pathogens. Compared to conventional chemical pesticides, biopesticides offer several advantages, including environmental safety, biodegradability, and target specificity, making them a sustainable and eco-friendly option for modern agriculture.



Types of Biopesticides

Biopesticides can be broadly classified based on their source of origin and the nature of the active compounds involved in their formulation. The major categories are described below-

Microbial Pesticides

Microbial pesticides are derived from naturally occurring microorganisms such as bacteria, fungi, and viruses. The bioactive compounds or metabolites produced by these organisms act against specific pest species, including insects, plant pathogens, and entomopathogenic nematodes. Microbial formulations that target insect pests are referred to as bioinsecticides, whereas those employing microorganisms—particularly fungi—for weed suppression are known as bioherbicides. Common bacterial entomopathogens belong to genera such as *Pseudomonas*, *Yersinia*, and *Chromobacterium*. Fungal biocontrol agents include species of *Beauveria*, *Metarhizium*, *Verticillium*, *Lecanicillium*, *Hirsutella*, and *Paecilomyces*. In addition, baculoviruses represent an important group of microbial pesticides due to their high host specificity. Their insecticidal activity is attributed to proteinaceous crystalline occlusion bodies, which are particularly effective against chewing insect pests, especially lepidopteran larvae. Entomopathogenic nematodes (EPNs), widely used as biological control agents, primarily belong to the genera *Heterorhabditis* and *Steinernema*. These nematodes maintain mutualistic associations with symbiotic bacteria such as *Photorhabdus* and *Xenorhabdus*. EPNs are considered environmentally safe and pose minimal risk to mammals and non-target organisms.

Biochemical Pesticides

Biochemical pesticides consist of naturally derived substances that manage pests through non-toxic or indirect modes of action, unlike synthetic chemical pesticides that cause direct mortality. Based on their functional properties, biochemical pesticides are categorized into pheromones (semiochemicals), plant-derived extracts and essential oils, and naturally occurring insect growth regulators.

Insect Pheromones: Insect pheromones are signaling chemicals naturally released by insects and are artificially synthesized for use in integrated pest management strategies. These compounds primarily function by disrupting mating behavior, thereby limiting successful reproduction and reducing pest populations. Pheromone-based control methods confuse insects by saturating the environment with pheromone signals, leading to ineffective mate location. Since they do not directly kill insects but instead modify insect behavior through olfactory interference, pheromones are not considered conventional insecticides.

Plant-Derived Extracts and Essential Oils: In recent years, extracts and essential oils obtained from plants have gained considerable attention as sustainable alternatives to synthetic insecticides. These natural products contain diverse bioactive constituents and exhibit multiple modes of action against insect pests. Depending on the plant species and the physiological traits of the target insect, plant extracts and essential oils may act as repellents, attractants, or antifeedants. They can also interfere with insect respiration, disrupt host plant recognition, inhibit egg-laying, and reduce adult emergence through ovicidal and larvicidal effects. The chemical composition of these extracts varies widely; however, neem and lemongrass oils are among the most widely used and commercially available plant-based biopesticides worldwide.

Insect Growth Regulators: Insect growth regulators (IGRs) disrupt essential physiological processes required for normal insect development, ultimately leading to pest suppression. These compounds are highly selective in their action and exhibit relatively low toxicity toward non-target organisms. Based on their mechanisms, IGRs are broadly classified into chitin synthesis inhibitors (CSIs) and hormone-related compounds, including juvenile hormone analogues and ecdysteroid mimics. IGRs are effective against a wide range of insect pests such as mosquitoes, cockroaches, and fleas; however, they are generally less lethal to adult insects. Instead, they interfere with reproduction, egg viability, and molting processes in immature stages. When combined with conventional insecticides, IGRs can also enhance control of adult insect populations while maintaining reduced environmental risk.

Genetically Modified Organism (GMO)–Based Products

GMO-derived biopesticides are produced using genetically engineered organisms in which specific pesticidal genes are introduced into plant genomes. These plants subsequently synthesize pest-protective compounds known as plant-incorporated protectants (PIPs). Among these, Cry proteins represent the earliest and most widely adopted class of insecticidal PIPs, introduced through the transfer of genes from the soil bacterium *Bacillus thuringiensis* (Bt.) into crop plants.

Mode of Action of Biopesticides

Biopesticides exhibit diverse modes of action depending on their biological origin and chemical nature. Their mechanisms involve direct or indirect interference with the growth, development, or survival of target pests and pathogens. Key mechanisms are described below-

Microbial Biopesticides

Microbial fungicides and bactericides primarily act by disrupting protein synthesis in target organisms. This may occur through inhibition of ribosomal function, such as binding to the 50S ribosomal subunit to block peptide transfer and chain elongation, as seen with compounds like blasticidin. Other agents, such as kasugamycin, interfere with aminoacyl-tRNA binding to the 30S and 70S ribosomal complexes, thereby inhibiting translation. Certain microbial herbicides act by blocking glutamine synthase activity in plants, leading to ammonia accumulation and subsequent cellular toxicity, as observed with bilanafos.

Biochemical Biopesticides

Biochemical pesticides are predominantly derived from plant sources. Over evolutionary time, plants have developed a wide range of secondary metabolites to defend against pests and pathogens. These bioactive compounds include alkaloids, steroids, phenolics, phenylpropanoids, terpenoids, and nitrogen-containing molecules. One of the earliest examples is nicotine, extracted from tobacco leaves in the seventeenth century and used as an insecticidal agent against beetles. Nicotine and similar plant-derived compounds are toxic to many herbivorous insects and are regarded as environmentally benign pesticides due to their effectiveness and comparatively low toxicity. Compounds such as azadirachtin and nicotine act by disrupting respiratory enzymes, interfering with insect hormonal regulation, or binding to sodium ion channels. In contrast, plant-derived microbicidal agents impair metabolic processes, compromise cell membrane integrity, and inhibit spore or conidial formation in pathogenic microorganisms.

GMO-Based Biopesticides

GMO-based biopesticides function through the expression of pesticidal genes within plant tissues, enabling the plant to produce its own protective compounds. A well-known example is the Bt. toxin, derived from *Bacillus thuringiensis*. When ingested by target insects, the delta endotoxins are activated by digestive proteases in the insect gut. The activated toxins bind to specific receptors in the midgut epithelial cells, causing pore formation, cellular swelling, membrane rupture, ion imbalance, and ultimately insect death.

Biopesticides from Algal and Cyanobacterial Sources

Microalgae and cyanobacteria offer promising alternatives for enhancing sustainability in agricultural systems. Several algal species produce biologically active metabolites with antimicrobial and pesticidal properties. Extracts or biomass derived from these organisms can be applied as natural biopesticides, contributing to crop protection while promoting plant growth. Filamentous cyanobacteria such as *Nostoc piscinale*, along with unicellular green algae including *Chlamydopodium fusiforme* and *Chlorella vulgaris*, have been reported to exhibit inhibitory activity against various plant pathogens.

Conclusion

The use of biofertilizers and biopesticides derived from bacteria, fungi, cyanobacteria, and microalgae plays a crucial role in improving soil fertility and promoting sustainable agricultural production through environmentally friendly technologies. The integration of microbial and algal biopesticides can reduce reliance on synthetic fertilizers and chemical pesticides, lower energy inputs, and help restore degraded agro ecosystems and wastelands. Although modern agriculture continues to depend on both chemical and biological pest control strategies, stricter regulatory frameworks have significantly encouraged the adoption of biopesticides. While numerous biopesticidal compounds have demonstrated potential under laboratory conditions, extensive field-based evaluations are essential to validate their effectiveness across different crops and agro-climatic regions. A balanced and judicious combination of conventional pesticides and biopesticides can provide optimal benefits to farmers and society. Continued research and development in the field of biopesticides remain vital to fully harness their potential for sustainable agriculture in the future.

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