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Role of biorational pesticides in sustainable agriculture system: Strategies and innovations

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Abstract
Biorational pesticides are manmade or natural substances found in animals, plants, microorganisms, and minerals, or their derivatives. Biorational pesticides include the microbiological pesticide *Bacillus thuringiensis* (Bt), neonicotinoids, avermectins, phenlpyrazoles, spinosyns, pyrroles, oxadiazines, and a variety of insect growth regulators. These compounds are efficient against the target pest, yet they are less harmful to natural adversaries and environmentally friendly. Biorational insecticides are gaining favor in this era of environmental knowledge and concern. The use of biorational products for insect pest. New techniques to pest control include the discovery of novel drugs that disrupt specific processes in insects, such as chitin synthesis inhibitors, juvenile hormone mimics, and ecdysone agonists. Furthermore, efforts have been made to develop compounds that selectively act on groups of insects by inhibiting or enhancing biochemical sites such as respiration (diafenthiuron), nicotinyl acetylcholine receptors (imidacloprid and acetamiprid), GABA receptors (avermectins), sucking pest salivary glands (pymetrozine), and others. Pesticides' severe environmental consequences, along with a resistance dilemma, have fueled demand for alternative pest management methods.

Keywords: Pesticides, microbes, environment, pest control, innovation

Introduction

Agriculture has always been the cornerstone of human civilization, supporting livelihoods, ensuring food security, and driving economic growth. However, the agricultural intensification that characterized the 20th century, especially during the Green Revolution, relied heavily on the use of synthetic chemical pesticides and fertilizers. While these inputs drastically increased global food production, they also generated significant ecological and health concerns. The excessive and indiscriminate use of chemical pesticides has led to pest resistance, loss of biodiversity, soil and water pollution, and adverse effects on non-target organisms, including beneficial insects, wildlife, and humans (Pathak *et al.*, 2022) [17]. The environmental costs of such intensive agriculture have raised global concerns about its long-term sustainability. Consequently, the 21st century has witnessed a paradigm shift in agricultural science and policy toward sustainable agriculture, an approach that balances productivity with environmental and social responsibility. Sustainable agriculture is defined as an integrated system of plant and animal production practices that satisfy human food and fiber needs while enhancing environmental quality and the natural resource base upon which agriculture depends. It emphasizes the maintenance of soil fertility, water conservation, biodiversity, and the judicious use of inputs. One of the most critical components of sustainable agriculture is sustainable pest management — the ability to manage pests effectively without causing ecological imbalance or health hazards. In this regard, the emergence and adoption of biorational pesticides have been recognized as a revolutionary step toward achieving environmentally friendly pest control solutions (Reddy, 2021) [18].

Biorational pesticides are a distinct class of pest control agents derived from natural materials or processes that exhibit high selectivity, safety, and efficacy against specific pest populations. The term “biorational” refers to their rational mode of action — targeting pests in ways that minimize harm to beneficial organisms and the environment. They include a wide array of products such as microbial pesticides (e.g., *Bacillus thuringiensis*, *Beauveria bassiana*), botanical insecticides (e.g., neem, pyrethrins), pheromones and semiochemicals, insect growth regulators (IGRs), and entomopathogenic nematodes. Unlike broad-spectrum chemical pesticides, these agents function through precise biochemical or physiological mechanisms, making them compatible with Integrated Pest Management (IPM) programs and organic farming systems (Singh & Gupta, 2024) [21].

The global movement toward sustainable pest management is being driven by multiple factors — regulatory restrictions on toxic chemicals, consumer demand for residue-free food, the rapid evolution of pest resistance, and the urgent need to mitigate environmental degradation. Many countries have tightened regulations on pesticide registration and promoted the use of eco-friendly alternatives, with international agencies such as the Food and Agriculture Organization (FAO) and the Organisation for Economic Co-operation and Development (OECD) emphasizing the development and adoption of biorational and biological control strategies (FAO, 2023) [8]. According to recent market reports, the global biopesticide industry is expanding rapidly, with projections suggesting a growth rate of over 12% annually, highlighting the growing acceptance and commercial viability of biorational technologies (Mawcha *et al.*, 2025) [14].

Biorational pesticides play a crucial role in maintaining the ecological balance within agricultural systems. They are often biodegradable, have short residual periods, and cause minimal disturbance to beneficial insects such as pollinators, parasitoids, and predators. Their mode of action — whether through microbial infection, enzymatic degradation, feeding deterrence, hormonal interference, or behavioral disruption — allows for effective pest suppression without compromising ecosystem services. Furthermore, several biorational agents, particularly microbial and plant-based products, enhance plant health by stimulating natural defense mechanisms or improving soil microbial diversity (Reddy, 2021) [18]. Thus, biorational pest management contributes not only to pest suppression but also to the overall resilience and sustainability of agroecosystems.

The integration of biorational strategies into pest management represents both an environmental necessity and a scientific innovation. In contrast to the "one-size-fits-all" approach of conventional pesticides, biorational technologies promote specificity and selectivity, ensuring that only target pests are affected while preserving non-target organisms. This specificity reduces the risk of pest resurgence and secondary outbreaks, which are common in systems heavily reliant on chemical controls. Moreover, because biorational agents operate through diverse and novel modes of action, they serve as valuable tools for resistance management, helping to delay or mitigate the development of pesticide-resistant pest populations.

Another significant advantage of biorational pesticides is their compatibility with modern innovations in agricultural biotechnology and precision farming. Advances in formulation technology, including nanoencapsulation and microencapsulation, have enhanced the stability, bioavailability, and controlled release of biorational products, thereby improving their efficacy under field conditions (Ayilara *et al.*, 2023) [2]. Additionally, the integration of digital pest monitoring systems, remote sensing, and data analytics allows farmers to apply biorational agents more accurately and efficiently, reducing wastage and improving cost-effectiveness. Such innovations bridge the gap between traditional ecological practices and cutting-edge technology, aligning well with the global vision of climate-smart agriculture.

From a socio-economic perspective, the adoption of biorational pesticides also supports rural livelihoods and local entrepreneurship, particularly in developing countries. Many biorational agents, such as neem extracts or microbial formulations, can be locally produced and customized according to regional pest dynamics. This decentralization of production encourages rural employment, reduces import dependency, and contributes to circular economy models in agriculture. Moreover, the increasing consumer awareness about organic and residue-free food is driving market incentives for farmers adopting biorational pest management practices.

Despite their potential, the widespread adoption of biorational pesticides still faces several challenges. These include limited awareness among farmers, inconsistent product quality, lack of standardization in formulation, and the relatively slower action of biorational agents compared to synthetic chemicals. Furthermore, regulatory barriers — such as lengthy registration processes and lack of harmonized international standards — often discourage investment and innovation in the biopesticide sector (FAO, 2023) [8]. Overcoming these challenges will require collaborative efforts involving policymakers, researchers, private industries, and farmers to develop supportive frameworks for product registration, market access, and capacity building.

Therefore, this review aims to explore the role of biorational pesticides in sustainable agriculture, focusing on the strategies, innovations, and mechanisms that underpin their success. It discusses the classification and mechanisms of various biorational agents, recent technological advancements enhancing their performance, and the policy and regulatory frameworks that influence their adoption. Ultimately, this paper underscores the importance of integrating biorational approaches into mainstream pest management systems as a cornerstone of environmentally responsible and economically viable agriculture.

Concept and Classification of Biorational Pesticides

Biorational pesticides are defined as pest management agents derived from natural sources such as microorganisms, plants, minerals, or biochemical compounds, exhibiting minimal environmental toxicity (EPA, 2020). They are designed to control pest populations through ecological mechanisms without harming non-target organisms or disrupting natural ecosystems. The major classes of biorational pesticides include microbial, botanical, biochemical pesticides, and insect growth regulators (IGRs). Microbial pesticides, such as those based on Bacillus thuringiensis (Bt), utilize microbial pathogens to infect and kill pests selectively. Botanical pesticides derive from plants and include compounds such as azadirachtin from neem and pyrethrins from chrysanthemum flowers. Biochemical pesticides involve pheromones, attractants, and repellents used for behavioral control, while IGRs disrupt insect development and reproduction (Isman, 2017) [11]. Biorational pesticides differ from conventional pesticides in that they are designed to exploit biological and ecological interactions rather than broad-spectrum toxicity (Isman, 2017) [11]. The growing market for biorationals reflects both regulatory support and consumer demand for organic food production Key attributes of biorational products include:

- Specificity to target pests
- Low mammalian toxicity
- Rapid degradation in the environment
- Compatibility with IPM and organic systems

Categories of Biorational Approaches

Botanical Pesticides: Botanical pesticides are derived from plant extracts containing bioactive compounds such as alkaloids, terpenoids, phenolics, and flavonoids. These compounds exhibit insecticidal, antifungal, and nematicidal properties (Isman, 2006) [10].

- **Neem: (*Azadirachta indica*):** Azadirachtin acts as an antifeedant, repellent, and growth disruptor (Mordue & Nisbet, 2000).
- **Pyrethrum: (*Chrysanthemum cinerariaefolium*):** Contains pyrethrins that rapidly knock down insects.
- **Rotenone, Nicotine, and Essential Oils:** Used as natural insecticides and repellents.

Microbial Biopesticides

Microbial agents constitute one of the most established categories of biorationals. These include bacteria, fungi, viruses, and protozoa that infect or suppress pest populations.

Major groups

- **Bacterial Biopesticides:** *Bacillus thuringiensis* (Bt) produces δ-endotoxins toxic to specific insect larvae.
- **Fungal Biopesticides:** *Beauveria bassiana*, *Metarhizium anisopliae*, and *Trichoderma spp.* act as entomopathogens or antagonists of plant pathogens.
- **Viral Biopesticides:** Nucleopolyhedroviruses (NPVs) and granuloviruses are highly host-specific against lepidopteran pests (Lacey *et al.*, 2015) [19].
- **Protozoan and Nematode Biopesticides:** Used mainly in soil pest control.

Biochemical Pesticides

Biochemical pesticides include naturally occurring compounds that control pests through non-toxic mechanisms—such as interfering with growth, reproduction, or behavior.

- **Insect Growth Regulators (IGRs):** Mimic insect hormones to disrupt molting and development (Dhadialla *et al.*, 2005) [5].
- **Plant Growth Regulators (PGRs):** Modify plant physiology to enhance resistance.
- **Allelochemicals:** Natural plant chemicals that inhibit pest or weed growth.
- **Elicitors and Inducers:** Compounds like salicylic acid trigger plant defense responses (Vlot *et al.*, 2009) [23].

Semiochemicals and Pheromone-Based Approaches

Semiochemicals are signaling molecules that mediate interactions among organisms. Pheromone-based pest management is one of the most successful biorational strategies.

- **Mating Disruption:** Synthetic sex pheromones prevent males from locating females (Witzgall *et al.*, 2010) [25].
- **Mass Trapping:** Pheromone-baited traps reduce pest populations.
- **Monitoring:** Detect pest outbreaks for timely intervention.

RNA-Based and Genetic Biorationals

Recent innovations include RNA interference (RNAi)-based bioinsecticides and genetically engineered microbial strains. These approaches offer species-specific pest suppression by silencing vital pest genes (Baum & Roberts, 2014) [3].

Double-stranded RNA (dsRNA) formulations targeting specific pest genes like *Snf7* in *Diabrotica virgifera*. High specificity and reduced off-target effects.

Natural Enemies and Biological Control Agents

Although sometimes treated separately, classical biological control agents such as parasitoids, predators, and entomopathogens are core components of biorational pest management.

- *Trichogramma spp.* (egg parasitoids)
- *Chrysoperla carnea* (green lacewing predator)
- *Aphidius colemani* (aphid parasitoid)

Biocontrol agents promote long-term pest suppression and ecological balance (Van Lenteren *et al.*, 2018) [22].

Comparative Advantages of different biorational approaches

Category	Example	Mode of Action	Target Specificity	Non-Target Effects
Bacteria	*Bacillus thuringiensis*	Midgut membrane disruption	High	Minimal
Fungi	*Beauveria bassiana*	Cuticle penetration, toxins	Moderate	Low
Virus	Nucleopolyhedrovirus	Cellular replication	High	Negligible
Botanicals	Neem, Pyrethrin	Feeding & hormonal disruption	Moderate	Low
IGRs	Diflubenzuron	Chitin synthesis inhibition	High	Minimal
Semiochemicals	Sex pheromones	Behavioral modification	Very High	None
Nematodes	*Steinernema* spp.	Bacterial symbiosis-induced toxemia	High	None

Role in Sustainable Agriculture

The integration of biorational pesticides contributes to environmental protection, food security, and long-term agricultural resilience. They reduce reliance on hazardous chemicals and improve soil and water quality by being biodegradable and less persistent in the environment (Aktar *et al.*, 2009) [1]. Their specificity toward target pests helps maintain beneficial insect populations and biodiversity. Additionally, biorational pesticides can be effectively integrated into Integrated Pest Management (IPM) systems, providing synergistic effects with biological control agents. They support organic farming practices and help meet consumer demand for pesticide-residue-free produce (Marrone, 2019) [15].

Mechanisms of Action

Biorational pesticides exhibit diverse mechanisms of action that reduce the risk of pest resistance. Microbial pesticides work by colonizing the pest body or gut, producing toxins or enzymes that disrupt normal physiological functions. Botanical pesticides may act as antifeedants, repellents, or growth inhibitors. For example, azadirachtin interferes with insect molting and reproduction, while pyrethrins target the insect nervous system. Biochemical pesticides such as pheromones alter pest behavior, preventing mating or attracting pests to traps. IGRs mimic or inhibit natural hormones to interrupt the growth cycle (Glare *et al.*, 2012) [9].

Strategies for Integration into Sustainable Systems

The successful implementation of biorational pesticides requires strategic integration into existing agricultural frameworks. This includes farmer training, policy incentives, and collaboration among research institutions, industry, and government. Farmers must be educated on correct usage, dosage, and timing to ensure optimal effectiveness. Governments should promote the use of biorational pesticides by offering subsidies and simplifying registration processes (FAO, 2021) [7]. Furthermore, combining these pesticides with precision agriculture tools such as drones and sensors can optimize their application and minimize wastage.

Innovations and Technological Advances

Technological advancements have expanded the potential of biorational pesticides. Nanotechnology has been employed to enhance the stability and slow release of active ingredients, increasing field efficacy (Sastry *et al.*, 2020) [20]. RNA interference (RNAi) technology has introduced gene-specific pest control by silencing critical genes in target species (Zotti *et al.*, 2018) [24]. Genetic engineering of microbial strains has improved virulence and persistence under field conditions. Additionally, smart delivery systems using biodegradable carriers and AI-based monitoring tools ensure precise and sustainable pest control.

Challenges and Limitations

Despite their numerous advantages, biorational pesticides face challenges that limit widespread adoption. Their production costs are often higher compared to synthetic chemicals, and they may have shorter shelf lives. Environmental sensitivity, inconsistent field performance, and limited awareness among small farmers remain barriers (Isman, 2017) [11]. Moreover, regulatory approval processes for biopesticides are often lengthy and complex, discouraging innovation and commercialization.

Future Prospects

The future of biorational pesticides lies in integrating them with cutting-edge technologies such as artificial intelligence, remote sensing, and biotechnology. Collaborative research should focus on developing cost-effective formulations with longer stability and higher efficacy. International policies and awareness campaigns can foster global adoption. As climate change reshapes pest dynamics, biorational approaches will be crucial for resilient and adaptive pest management strategies.

Conclusion

Biorational pesticides represent an essential shift toward sustainable pest management and environmental protection. Their specificity, biodegradability, and compatibility with IPM systems make them ideal alternatives to synthetic chemicals. While challenges remain, continuous innovation and policy support can transform biorational pesticides into mainstream agricultural tools, ensuring food safety and ecological balance.

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