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REVIEW ARTICLE

Nanotechnology Enhanced Biocontrol, Growth Promoters, And Regulators for Sustainable Pest Management

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ABSTRACT

Pest and disease management is a global concern in modern agriculture. The overuse of chemicals use, environmental degradation, biodiversity loss, and pesticide resistance To meet the growing demand for sustainable food production, new approaches to pest control are needed to lessen their negative effects on the environment without compromising crop yields. This paper discusses sustainable pest and disease management in agriculture using biocontrol agents, plant growth-promoting rhizobacteria (PGPR). Biocontrol species suppress whiteflies, root-knot nematodes, and fungal diseases while improving plant development and resilience. PGPR strains like *Pseudomonas fluorescens* and *Bacillus aryabhatai* boost nutrient uptake, stress tolerance, and plant defense mechanisms like ISR, phytohormone synthesis, and nutrient solubilization. Biological treatments are important, but nano-emulsions, fungicides, and insecticides are still important in pest management, especially when paired with biological methods to limit environmental impact. Integrated Pest Management (IPM) is applied as a holistic, sustainable approach to pest and disease control in agriculture that reduces chemical use and promotes ecological balance. This review article provides a comprehensive foundation for future research by highlighting current knowledge gaps, proposing innovative methodologies, and offering insights into sustainable strategies that can be further developed to enhance agricultural productivity.

Keywords: Sustainable agriculture, Biopesticides, Synergists, Pesticide resistance, Biocontrol, PGPR..

INTRODUCTION

Agriculture, which provides the world's food, is struggling with poor health and pests (Li and Wang, 2024). Overusing chemical pesticides for problem solutions has caused pesticide resistance, environmental harm, and health issues, hence new sustainable and integrated pest management (IPM) methods are needed. Arshad *et al.* (2024) suggested that phytoextracts, rather than harmful fungicides, could be a more effective method of treatment.

Given these issues, plant growth-promoting rhizobacteria (PGPR) and biocontrol agents are becoming more popular as eco-friendly pesticide alternatives (Fiaz *et al.*, 2023; Chaudhary *et al.*, 2024). Biocontrol agents including *Trichoderma harzianum*, *Bacillus subtilis*, and *Pseudomonas fluorescens* have suppressed soil-borne bacterial, nematode and fungal infections (Kumar *et al.*, 2024; Al-Rawashdeh, 2024).

PGPRs, such as *Bacillus* and *Paenibacillus* strains, boost plant growth, nutrient absorption, stress resilience, and biotic and abiotic stress resistance. These microorganisms boost nitrogen fixation, root growth, and crop resilience in sustainable agricultural systems (Sarkar *et al.*, 2017). Nano-emulsions and other sophisticated agrochemical formulations have joined biological agents (Hajji-Hedfi and Chhipa, 2021). These plant extract or essential oil compositions have showed promise in enhancing the stability and bioavailability of plant-based insecticides, making them more efficient at managing insect pests and fungal illnesses (Gondal *et al.*, 2024; Nisar *et al.*, 2024). Chemical, biological, and plant growth-promoting rhizobacteria are employed in a comprehensive pest management strategy to diminish chemical usage and enhance crop health and productivity. Lambda cyhalothrin and piperonyl butoxide (PBO) synergists can increase efficacy, reduce resistance, and promote sustainable pest control in mango (Dash *et al.*,

2024). Multidimensional pest management using biological and low-impact chemicals (Neem Oil, Insecticidal Soaps, Horticultural Oils) in IPM systems increases crop yield and disease resistance. Field adaptation of biocontrol and integrated techniques and pest populations resistant to new technologies remain issues. Over time pest may develop resistance to the biocontrol agents and due to unpredictable environmental conditions they may not perform consistently. Future research may develop crop-specific microbial formulations, analyse chemical-biological interactions, and optimise biological agent field use (Fig. 1). Soil health and genetic resistance research can help establish resilient agricultural systems that preserve the environment and provide food security. Biocontrol, plant growth-promoting rhizobacteria (PGPR), and new agrochemical approaches are examined for their efficacy, environmental impact, and potential for sustainable pest management (Tyagi *et al.*, 2024).

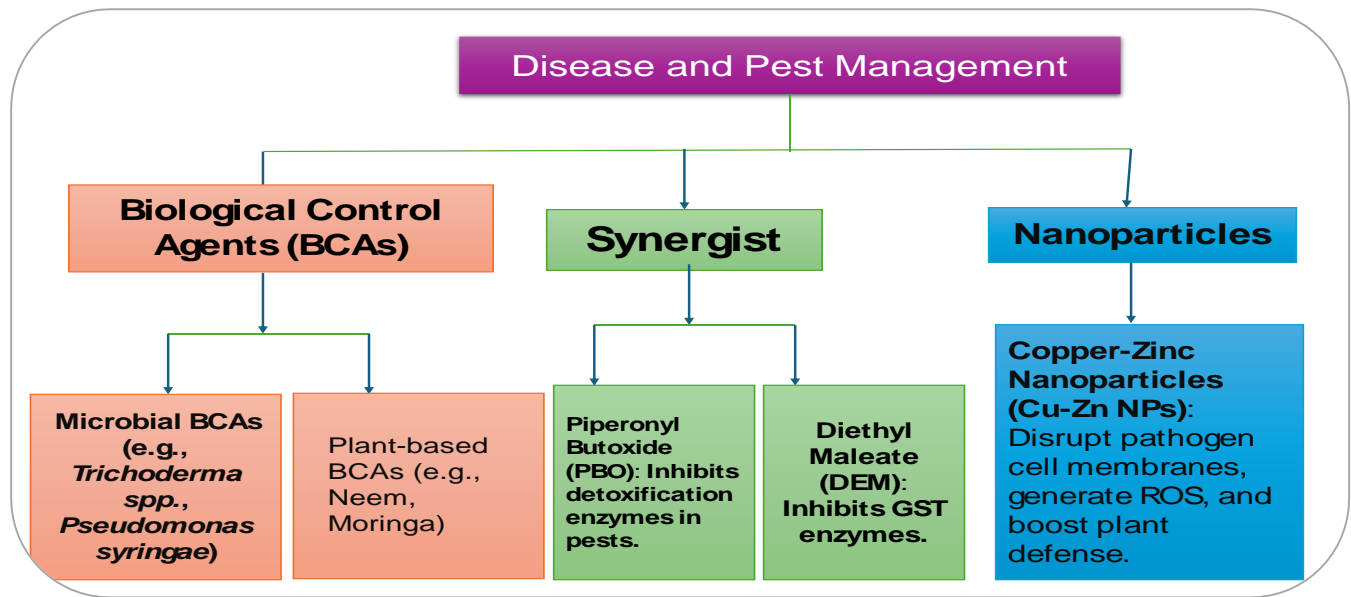


Figure 1. Flowchart of disease and pest management.

Integrated disease management (IDM): Sustainable agriculture requires multiple disease management strategies (Fadeel *et al.*, 2024). These methods include biocontrol agents, plant extracts, nanoparticles, and cultural practices (Table 2). Biocontrol agents and chicken manure can treat soil-borne diseases like *Fusarium oxysporum* (Shakeel *et al.*, 2023). Chemical and biological techniques have controlled Brassica crop diseases including citrus melanose and clubroot (Umer *et*

al., 2024). A comprehensive plant disease management strategy using resistant plant cultivars, biocontrol chemicals, and perfect environmental conditions is possible. Combining these methods can make agriculture more resilient to climate change and diseases.

Biological control and biocontrol agents: Plant disease biocontrol agents offer a sustainable alternative to synthetic pesticides. Numerous studies suggest that *Pseudomonas syringae* and *Trichoderma* spp. inhibit

Macrophomina phaseolina and *Fusarium oxysporum*. These drugs inhibit fungus by mycoparasitism, antifungal chemical synthesis, and resource competition (Fatima, 2023; Table 1). When one fungus parasitises another, its cell wall breaks down and growth stops. *Trichoderma* spp. chitinases and glucanases degrade *Fusarium* cell walls (Akhtar, 2024). *Pseudomonas syringae*'s syringomycin, which destroys fungal membranes, and antioxidant responses help plants fight *Fusarium* species (Muthu *et al.*, 2022). *Trichoderma harzianum* produces chitinase, which breaks down fungal cell walls and helps plants grow and resist illness (Loc *et al.*, 2020). Improved nutrient absorption and phytohormone synthesis by endophytes such *Paenibacillus polymyxa* and *Bacillus subtilis* promote plant development. These biocontrol bacteria reduce pathogens and improve cotton and chilli disease resistance (Khan *et al.*, 2021).

Biocontrol mechanism of fungal pathogens: A key mechanism of fungal BCAs is competition for space and nutrients. Many biocontrol fungi colonize plant roots and leaves, outcompeting pathogenic fungus for water, oxygen, and nutrients. Competitive inhibition can prevent or reduce infection by limiting dangerous fungus (Harman *et al.*, 2004). Antibiosis occurs when biocontrol

fungi create pathogen-toxic secondary metabolites. These bioactive chemicals kill or inhibit fungal infections. The antibiosis mechanism produces VOCs and non-volatile metabolites that disturb pathogenic fungi's metabolism (Sharma *et al.*, 2014). Biocontrol fungi that induce systemic resistance in plants boost nature's defenses against diseases. The plant's immune system produces defense enzymes, phytoalexins, and other secondary metabolites that make it resistant to infection (Vinale *et al.*, 2008).

Biocontrol mechanism of bacterial pathogens: A diverse array of bacterial genera, such as *Agrobacterium*, *Alcaligenes*, *Arthrobacter*, *Bacillus*, *Enterobacter*, *Erwinia*, *Pseudomonas*, *Rhizobium*, *Serratia*, *Stenotrophomonas*, *Streptomyces*, and *Xanthomonas*, have been documented to exhibit protective activity against fungal and bacterial pathogens in plants. These bacteria employ various strategies to restrict the development of plant diseases. The modes of action encompass colonization of infection sites, competitive exclusion of pathogens, antagonistic activity through the release of potent antimicrobials such as antibiotics or cell wall lytic enzymes, and the establishment of plant resistance (Lugtenberg *et al.*, 2009; Berendsen *et al.*, 2012; Montesinos *et al.*, 2009).

Table 1. Effects and mechanism in disease and pest control

Mechanism	Description	Citations
Mycoparasitism	One fungus parasitizes another, breaking down its cell wall through enzymes like chitinase and glucanase, inhibiting growth.	Schouttetten <i>et al.</i> (2024)
Antibiosis	Production of toxic metabolites by microbes that inhibit the growth of pathogens or pests.	Saska and Skuhrovec (2024)
Induced Systemic Resistance (ISR)	Activation of plant immune responses, triggering the production of defense proteins and antimicrobial compounds to resist pathogen infection.	Sharma <i>et al.</i> (2024)
Synergistic effects	The combined action of chemicals and natural compounds (e.g., insecticides + plant extracts or synergists) that enhance the effectiveness of pest control.	Reddy and Chowdary (2021)
Enzymatic detoxification	Pathogens or pests detoxify chemicals via enzymes like cytochrome P450, GST, or esterases, leading to resistance.	Naseer <i>et al.</i> (2024)
Nanoparticles action	Nanoparticles, such as Cu-Zn NPs, disrupt pathogen cell membranes, generate reactive oxygen species (ROS), and stimulate plant defence enzymes.	Devi <i>et al.</i> (2025)
Antioxidant enzyme activity	Enzymes like superoxide dismutase (SOD), peroxidase (PO), and catalase (CAT) neutralize ROS to mitigate damage during stress or pathogen attack.	Novikova <i>et al.</i> (2024)
Biocontrol by competition	Beneficial microbes, like <i>Pseudomonas syringae</i> , outcompete pathogens for nutrients and space, suppressing pathogen growth.	Sahoo <i>et al.</i> (2024)
Enzyme inhibition by synergists	Insecticide efficacy is enhanced by synergists like Piperonyl Butoxide (PBO), which inhibit cytochrome P450, a detoxifying enzyme.	Joseph <i>et al.</i> (2024)

Use of plant-based extracts in disease control: Plant extracts are a natural alternative to fungicides and

pesticides for managing fungal infections and stored product pests (Al-Obaidi and Alsawaf, 2024; Rehman *et al.*, 2023). Chinaberry (*Melia azedarach*), basil (*Ocimum basilicum*), and neem (*Azadirachta indica*) extracts were found to be effective antifungal agents against the cowpea beetle (*Callosobruchus maculatus*). Plant extracts contain bioactive compounds such as azadirachtin, alkaloids, and saponins that hinder insect growth (Toka *et al.*, 2023). Azadirachtin in neem extract mimics insect molting hormones (ecdysteroids), inhibiting growth, eating, and oviposition (Malik *et al.*, 2023).

Alkaloids in Chinaberry and oleander bioactives affect larval and pupae metabolism, increasing mortality (Alhadidy, 2023). Plant extracts may also cure fungal infections like *Alternaria solani*, which causes tomato early blight. Ginger and marigold extracts work synergistically with chemical fungicides to combat disease and reduce pesticide use (Mulyati *et al.*, 2024).

Nanotechnology in disease management:

Nanotechnology is an interdisciplinary research field that utilizes the fundamental methodologies of many other fields, including engineering, chemistry, physics, and life sciences, to the development of innovative strategies to manipulating minute particles ultimately leading to the synthesis of NPs. In recent years, there has been more and more interest in using NPs in agriculture to help plants grow faster, take in more nutrients, and resist phytopathogens (Malandrakis *et al.*, 2022; Ali *et al.*, 2024; Usman *et al.*, 2024). Nanoparticles, especially plant-derived ones, have been studied as a novel plant disease treatment. Ali *et al.* (2024) found that neem-extracted Cu-Zn hybrid nanoparticles had better antibacterial activity against *Xanthomonas campestris*. These nanoparticles

damage bacterial cell membranes and boost plant defenses by enhancing antioxidant enzyme activity (Francis *et al.*, 2024). Fungal and bacterial infections have been treated with nanoparticles. Copper and zinc nanoparticles mediated by neem may treat sugarcane diseases including red rot and Fusarium wilt (Almajed *et al.*, 2024; Nisar *et al.*, 2024; Kashyap *et al.*, 2024). Copper and zinc nanoparticles increase disease control and provide a sustainable fungicide alternative (Malandrakis *et al.*, 2019). To reduce oxidative stress and promote plant health, antioxidant enzymes like catalase (CAT), peroxidase (PO), and superoxide dismutase (SOD) neutralize damaging reactive oxygen species (ROS) created during pathogen invasion (Thepbandit *et al.*, 2024).

Mechanism of nanoparticles to control: Nanoparticles control pathogens through several mechanisms that disrupt their cellular integrity and functions. First, they can physically damage pathogen cell membranes, particularly those with sharp edges or high surface reactivity, which penetrate the membrane and cause leakage of cellular contents. Additionally, nanoparticles generate reactive oxygen species (ROS), such as hydroxyl radicals and superoxide ions, which induce oxidative stress and damage key cellular components like membranes, proteins, and DNA. This oxidative damage overwhelms the pathogen's defense systems, leading to cell death. Furthermore, nanoparticles interfere with crucial metabolic processes, including energy production, biosynthesis, and DNA replication, while also disrupting quorum sensing mechanisms that regulate behaviors like biofilm formation. Together, these mechanisms enable nanoparticles to effectively control a wide range of pathogens (Ali *et al.*, 2024; Olawade *et al.*, 2024).

Table 2. Mode of action of nanoparticles

Nanomaterial	Target insect	Mode of action	References
Ag nanoparticles (0.2, 0.5, and 1 mg/l)	<i>Chironomus riparius</i>	GST genes up- or downregulated, according to tested concentration and duration of exposure, highest mRNA expression was in delta 3, Sigma 4 and Epsilon1 GST class	Nair and Choi (2011)
Ag nanoparticles (500 to 4000 mg/l)	<i>Spodoptera litura</i>	Nano-induced oxidative stress in moth larval guts, with enhanced antioxidant enzyme levels	Yasur and Usha-Rani (2015)
Nanostructured Al ₂ O ₃ (60-500 ppm)	<i>Sitophilus oryzae</i>	Bind to the beetle cuticle due to triboelectric forces, sorbing its wax layer by surface area phenomena, resulting in insect dehydration	Stadler <i>et al.</i> (2017)
Carbon black and multiwalled nanotubes (3.3 and 3.1 mg, respectively)	<i>Drosophila melanogaster</i>	Strong adherence of the nanomaterials to the fly body parts, leading to impaired motor functions and insect mortality	Liu <i>et al.</i> (2009)
SiO ₂ nanoparticles	stored product pests	pests Physio-sorbed by the insect cuticular lipids, causing significant damages, followed by the insect's death	Barik <i>et al.</i> (2008)

Synergistic effects and resistance mechanisms:

Overuse of insecticides, especially in pests like the mango leaf hopper (*Amritodus atkinsoni*), is blamed for insecticide resistance (Reddy, 2024). Synergists like diethyl maleate (DEM) and piperonyl butoxide (PBO) might boost pesticide efficacy by blocking detoxifying enzymes such mixed-function oxidases (MFOs) (Muthusamy *et al.*, 2024). Synergists restore pesticide sensitivity, making them essential for fighting resistance. Detoxing Enzymes: Pesticide-metabolizing enzymes such cytochrome P450, GST, and esterases help insects gain resistance (Bendele *et al.*, 2022). Synergists improve pesticide efficacy by inhibiting enzymes (Zhu *et al.*, 2024). Enzymatic detoxification by cytochrome P450, esterases, and glutathione-S-transferases is also crucial in pest

resistance (Khan *et al.*, 2021).

Environmental stress and plant defence: Temperature, salinity, and drought stress greatly impact plant disease dynamics. Temperature affects pesticide efficacy and resistance (Gabash *et al.*, 2023). Temperatures can increase pesticide toxicity or detoxify, diminishing efficacy. ROS, phytohormones including ABA, and stress-associated proteins are produced by plants in response to drought and salinity. Plant metabolic processes help them fight infections and environmental challenges. Citrus seedlings challenged by dehydration and salinity adapted with thicker cuticles and tannin cells. Stress-induced ROS increase resistance via oxidative stress pathways. They protect plants by boosting antioxidant and systemic resistance (Atiq *et al.*, 2020; Tahir *et al.*, 2023, 2024).

Table 3. Natural compounds and biocontrol agents used for pest management

Biocontrol agent/natural compound	Target pathogen/pest	Mode of action	Citations
<i>Trichoderma</i> spp.	<i>Fusarium</i> species, <i>Macrophomina phaseolina</i>	Mycoparasitism, production of chitinases and glucanases to break down fungal cell walls.	Parihar <i>et al.</i> (2024)
<i>Pseudomonas syringae</i>	<i>Fusarium oxysporum</i> , <i>Sclerotium rolfsii</i>	Antagonistic activity through syringomycin production, disrupts fungal membranes and induces plant defense through ROS production.	Goswami <i>et al.</i> (2021); Tripathy <i>et al.</i> (2023)
<i>Bacillus</i> spp.	<i>Fusarium oxysporum</i> , <i>Verticillium</i> wilt	Production of lipopeptides and volatile organic compounds (VOCs) that disrupt fungal cell membranes and induce systemic resistance in plants.	Alamoudi (2024)
Neem (<i>Azadirachta indica</i>)	Various pests and diseases, including <i>Bemisia tabaci</i>	Azadirachtin disrupts insect molting and growth, acting as a feeding deterrent and oviposition inhibitor.	Hassan <i>et al.</i> (2024)
Chitosan	<i>Moniliophthora roreri</i> (cocoa pathogen)	Inhibits pathogen cell walls, promotes plant defense, increases antioxidant enzymes, and enhances photosynthesis.	Lyoufsi <i>et al.</i> (2024); Rodriguez <i>et al.</i> (2024)
Copper-Zinc nanoparticles (Cu-Zn NPs)	<i>Xanthomonas campestris</i> , <i>Fusarium oxysporum</i>	Disrupts pathogen membranes, generates ROS, and stimulates plant defenses by increasing antioxidant enzyme activities.	Victoria <i>et al.</i> (2025)
Ginger extract	<i>Alternaria solani</i> (tomato early blight)	Disrupts fungal cell walls, induces oxidative stress through gingerols and shogaols compounds.	Zhang <i>et al.</i> (2024)
Moringa extract	<i>Bemisia tabaci</i> (cotton whitefly)	Contains flavonoids and alkaloids, acts as a neurotoxic agent and feeding deterrent to whiteflies.	Saini and Gupta (2024)
Clove extract	<i>Alternaria alternata</i> (Aloe vera leaf spot)	Eugenol in clove extract disrupts fungal membranes, inhibiting fungal growth and spore germination.	Nagamma <i>et al.</i> (2019)
Basil extract	<i>Alternaria solani</i> (tomato early blight)	Contains antimicrobial compounds like phenolics that inhibit fungal metabolism and cell growth.	Ul Haq <i>et al.</i> (2024)

CONCLUSION

Agriculture sustainability depends on IPM systems that include biological, chemical, and cultural techniques. These methods reduce pesticide use, which hurts humans, animals, and ecosystems, and improve pest management. In response to global environmental concerns, IPM solutions may increase agricultural output, biodiversity conservation, and food security by promoting ecological balance. PGPR strains increase plant nutrient uptake, stress tolerance, and systemic resistance. *Bacillus subtilis*, *Trichoderma harzianum*, and *Cryosperla* spp. combat pests and diseases, and improve plant health, resistance, and growth. Nanotechnology in pest control appears promise. Improving insecticide, fungicide, and fertilizer nano-formulations improve active component stability, bioavailability, and

effectiveness. Non-chemical nano-emulsions reduce pesticide use and boost efficiency. Genomic and molecular methods may sharpen biological agents to control pests and diseases.

Precision agriculture and data-driven pest control provide alternatives. Sensors, drones, and satellites will improve farmer pest, soil, and crop monitoring. These more precise, timely, and sustainable pest control methods will help them optimise resource use and limit environmental harm. Finally, biocontrol agent, PGPR, and synthetic chemical interactions in IPM systems must be studied for long-term crop protection and environmental stewardship. Due to climate change, insect resistance, and increased food demand, policymakers, agricultural stakeholders, and academics must develop integrated, adaptable pest management methods.

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