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ECO-COMPATIBLE AGRICULTURE THROUGH MICROBIAL METABOLITES: ADVANCES IN BIOSTIMULANT AND BIOPROTECTANT STRATEGIES

Ajay Kumar Singh[1] and Kamal Prasad[2]*

[1]Director Research, A G Bio Systems Private Limited, Hyderabad, Telangana, India.

[2]*VP–R&D, Privi Life Science, Research and Development, Navi Mumbai, Maharashtra, India.

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***Corresponding Author: Kamal Prasad**

Director Research, A G Bio Systems Private Limited, Hyderabad, Telangana, India.

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ABSTRACT

Microbial secondary metabolites are emerging as vital agents in sustainable agriculture, offering eco-compatible alternatives to conventional agrochemicals. Produced by diverse microorganisms—including bacteria, fungi, and actinomycetes—these bioactive compounds, though not essential for microbial survival, exert profound influences on plant physiology and development. Acting as signaling molecules, phytohormone modulators, and antimicrobial agents, they enhance nutrient assimilation, stimulate root system architecture, and activate defense responses against biotic and abiotic stresses. As biostimulants, microbial metabolites promote plant vigor by modulating hormonal pathways, improving stress resilience, and fostering beneficial plant–microbe interactions. As bioprotectants, they suppress pathogens through mechanisms such as induced systemic resistance (ISR), quorum sensing disruption, and direct antimicrobial activity. Their multifunctional nature positions them as integral components of integrated crop management systems that emphasize environmental stewardship, soil health, and long-term productivity. This review consolidates current insights into the classification, biosynthetic pathways, and functional roles of microbial secondary metabolites in agriculture. It further examines advances in formulation technologies, field-level applications, and evolving regulatory frameworks, while identifying key challenges and future research directions. Harnessing these natural compounds can accelerate the transition toward resilient, resource-efficient, and ecologically balanced farming systems.

KEYWORDS: Microbial metabolites; biostimulants; bioprotectants; sustainable agriculture; induced systemic resistance (ISR); quorum sensing; plant–microbe interactions; soil health; crop resilience; integrated crop management.

1. INTRODUCTION

The escalating global demand for sustainable and environmentally responsible agricultural practices has catalyzed a paradigm shift from reliance on synthetic agrochemicals toward biologically derived inputs. Among these, microbial biostimulants and bioprotectants have emerged as promising tools to enhance crop productivity while safeguarding ecological integrity. Within this domain, microbial secondary metabolites (MSMs) have garnered significant attention due to their multifunctional roles in promoting plant health, resilience, and long-term soil fertility (Ben Mrid et al., 2021; Marks et al., 2025).

MSMs encompass a diverse array of chemical classes—including alkaloids, terpenoids, phenolics, and peptides—that are synthesized during specific microbial developmental stages or in response to environmental stressors such as nutrient limitation, interspecies competition, and host–microbe interactions (Dinglasan et al., 2024). Unlike primary metabolites, which are essential for microbial growth and reproduction, secondary metabolites serve as specialized ecological tools that enable microorganisms to adapt, compete, and thrive in complex environments. Their ecological functions translate into profound agricultural benefits, making them valuable agents in crop management systems.

In agricultural contexts, microbial secondary metabolites (MSMs) influence plant physiology through several mechanisms: they enhance nutrient acquisition and assimilation by acting as chelators or mobilizers that increase the bioavailability of essential elements such as iron, phosphorus, and nitrogen; they activate plant defense systems by triggering immune responses, including induced systemic resistance (ISR), which fortifies crops against pathogens and pests; they mitigate abiotic stresses through compounds like phenolics and terpenoids that provide antioxidant activity, regulate osmotic balance, and improve tolerance to drought, salinity, and temperature extremes (Vinale et al., 2017; Raaijmakers & Mazzola, 2016); and they modulate microbial communities via peptides such as lipopeptides and bacteriocins, which exhibit strong antimicrobial properties, suppress soil-borne diseases, and foster beneficial microbial consortia (Ongena & Jacques, 2008).

The integration of MSMs into crop management strategies offers a multifaceted approach to reducing chemical inputs, improving soil health, and enhancing crop resilience under the pressures of climate variability (Calvo et al., 2014). Their specificity, bioactivity at low concentrations, and ecological compatibility position them as vital components of next-generation biostimulant and bioprotectant formulations. Moreover, advances in omics technologies, synthetic biology, and formulation science are accelerating the discovery, optimization, and application of these metabolites in field conditions.

As research continues to unravel the biosynthetic pathways, regulatory networks, and ecological functions of MSMs, their role in agriculture is expected to expand significantly. They represent not only a sustainable alternative to conventional agrochemicals but also a cornerstone in the evolution of resilient, resource-efficient, and climate-smart farming systems (Sharma et al., 2023). This review aims to consolidate current knowledge on microbial secondary metabolites, highlight their biostimulant and bioprotectant potentials, and explore future directions for their integration into sustainable agricultural practices.

2. Classification of Secondary Metabolites

Secondary metabolites are structurally diverse compounds synthesized by microorganisms and plants that play pivotal roles in ecological interactions, defense, and signaling (Table 1). Unlike primary metabolites, which are directly involved in growth and reproduction, secondary metabolites are often produced under specific developmental stages or environmental conditions. Their ecological functions—ranging from chemical defense to interspecies communication—translate into significant contributions to plant health, resilience, and adaptation (Elshafie et al., 2023; Saini & Yadav, 2018).

2.1 Alkaloids

Alkaloids are nitrogen-containing compounds widely recognized for their defensive roles in plants. They often act as potent deterrents against herbivores and pathogens due to their toxicity and bioactivity. For example, nicotine, historically used as a natural pesticide, disrupts insect nervous systems, while indole alkaloids such as tryptamine influence plant growth and stress responses (Naji et al., 2024). In agriculture, alkaloids are valued for their dual role as natural pesticides and modulators of plant physiology.

2.2 Terpenoids

Terpenoids, derived from isoprene units, represent one of the largest classes of secondary metabolites. They include both growth regulators and defense molecules. Gibberellins regulate plant growth and development, while compounds such as saponins disrupt pathogen membranes, exhibiting antimicrobial and antifungal activity. Other terpenoids, like menthol and taxol, contribute to plant defense and have pharmaceutical relevance (Elshafie et al., 2023; Naji et al., 2024). Their structural diversity and bioactivity make terpenoids central to both ecological adaptation and biotechnological exploitation.

2.3 Phenolics

Phenolic compounds—including flavonoids, tannins, and lignins—are synthesized via the shikimate and phenylpropanoid pathways, and they perform multiple functions such as mitigating oxidative stress through antioxidant activity, shielding plant tissues from radiation damage by providing UV protection, reinforcing structural integrity via lignin deposition in cell walls, and enhancing pathogen resistance by inhibiting microbial colonization; thus, phenolics act as multifunctional agents that improve tolerance to abiotic stress while simultaneously strengthening plant defenses (Naji et al., 2024; Elshafie et al., 2023).

2.4 Peptides

Peptide-based metabolites, particularly microbial lipopeptides such as surfactin and fengycin, exhibit surfactant properties that disrupt pathogen membranes and elicit plant immune responses without causing disease. These compounds are notable for their ability to trigger Induced Systemic Resistance (ISR), priming plants for enhanced defense against subsequent pathogen attacks. Additionally, bacteriocins—ribosomally synthesized antimicrobial peptides—play a crucial role in suppressing soil-borne pathogens and shaping beneficial microbial communities in the rhizosphere (Saini & Yadav, 2018; Elshafie et al., 2023).

Table 1. Classification of Secondary Metabolites with Examples and Functions

Class	Examples	Function in Plants	References
Alkaloids	Indole alkaloids (e.g., tryptamine), Nicotine	Chemical deterrents against herbivores and pathogens; modulation of growth and stress responses	Naji et al. (2024); Saini & Yadav (2018)
Terpenoids	Gibberellins, Saponins, Menthol, Taxol	Regulate growth and development; antimicrobial, antifungal, and insecticidal properties	Elshafie et al. (2023); Naji et al. (2024)

Phenolics	Flavonoids, Tannins, Lignins	Antioxidant protection, UV shielding, tolerance to abiotic stress, structural integrity, pathogen resistance	Naji et al. (2024); Elshafie et al. (2023)
Peptides	Lipopeptides (e.g., surfactin, fengycin), Bacteriocins	Direct inhibition of microbial pathogens; activation of Induced Systemic Resistance (ISR)	Saini & Yadav (2018); Elshafie et al. (2023)

3. Biostimulant Activity of Secondary Metabolites

Microbial secondary metabolites (MSMs) play a pivotal role in enhancing plant growth and development by functioning as natural biostimulants. Unlike synthetic agrochemicals, these compounds act in subtle yet powerful ways, influencing a wide spectrum of physiological processes. They often mimic or modulate plant hormones, improve nutrient availability, and strengthen tolerance to environmental stresses. Their biostimulant activity can be categorized into several key functions (Fig 1):

3.1 Enhancing Nutrient Uptake

One of the most critical contributions of MSMs is the facilitation of nutrient acquisition. Certain microbes produce siderophores, low-molecular-weight chelating agents that bind insoluble iron (Fe^{3+}) in the soil and convert it into bioavailable forms. Iron is indispensable for chlorophyll biosynthesis, respiration, and enzymatic activity, yet it often exists in inaccessible complexes. Siderophore-producing bacteria such as *Pseudomonas spp.* and *Bacillus spp.* significantly improve iron uptake, particularly under deficiency conditions, thereby enhancing photosynthetic efficiency and plant vigor (Ahmed & Holmström, 2014). Beyond iron, microbial metabolites also mobilize phosphorus, zinc, and manganese, further contributing to nutrient balance and crop productivity.

3.2 Stimulating Root Architecture

Secondary metabolites with auxin-like activity, such as indole-3-acetic acid (IAA) analogs, profoundly influence root system development. They promote root elongation, lateral root initiation, and root hair proliferation, thereby expanding the soil exploration capacity of plants. Enhanced root morphology improves water absorption and nutrient uptake efficiency, creating a more resilient plant system. Microbial strains such as *Azospirillum brasilense* and *Rhizobium spp.* are well-documented producers of IAA-like compounds, leading to improved root system architecture and overall plant biomass accumulation (Spaepen et al., 2007). This root stimulation also fosters beneficial rhizosphere interactions, strengthening plant–microbe symbioses.

3.3 Improving Abiotic Stress Tolerance

Abiotic stresses—including drought, salinity, and temperature extremes—pose major challenges to crop productivity. MSMs mitigate these stresses through the production of osmoprotectants (e.g., proline derivatives, glycine betaine) that stabilize proteins, membranes, and cellular structures. These compounds maintain osmotic balance, reduce oxidative damage by scavenging reactive oxygen species (ROS), and preserve metabolic activity under adverse conditions. Microbes such as *Halomonas spp.* and *Bacillus megaterium* have demonstrated the ability to produce stress-alleviating metabolites that enhance plant resilience (Yang et al., 2009). Additionally, phenolic metabolites contribute antioxidant activity, further protecting plants from oxidative stress.

3.4 Modulating Hormonal Pathways

Microbial metabolites also interact with plant hormonal networks, fine-tuning growth and developmental responses. For instance, gibberellin-like terpenoids produced by *Fusarium fujikuroi* and *Penicillium spp.* stimulate stem elongation, seed germination, and flowering. Similarly, microbial metabolites can modulate ethylene levels, reducing stress-induced senescence, or influence cytokinin activity, enhancing nutrient mobilization and delaying leaf aging (Hamayun et al., 2010). By integrating into endogenous hormone signaling pathways, these metabolites orchestrate balanced growth responses, ensuring plants adapt effectively to both favorable and stressful environments.

3.5 Strengthening Plant–Microbe Interactions

Beyond direct physiological effects, MSMs act as signaling molecules that strengthen beneficial plant–microbe interactions. Compounds such as quorum-sensing inhibitors regulate microbial communication, preventing pathogenic colonization while promoting symbiotic associations. This signaling fosters the establishment of beneficial consortia in the rhizosphere, enhancing nutrient cycling, disease suppression, and long-term soil fertility.

Collectively, microbial secondary metabolites function as natural biostimulants by enhancing nutrient uptake, stimulating root development, improving abiotic stress tolerance, modulating hormonal pathways, and fostering beneficial plant–microbe interactions. Their multifunctional roles not only improve crop performance but also contribute to sustainable agricultural practices by reducing dependence on synthetic inputs and enhancing ecological resilience.

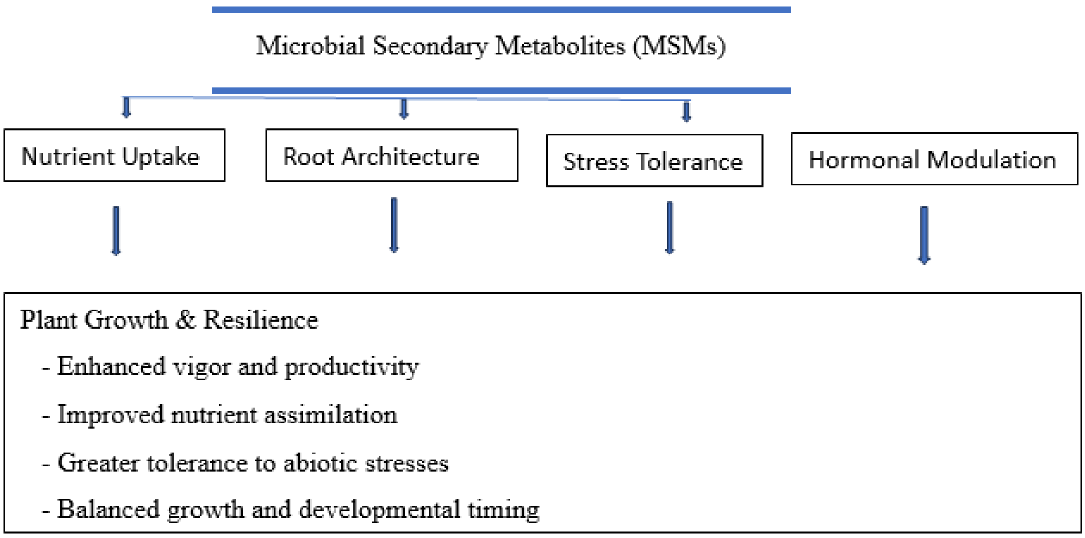

Fig. 1 Schematic Flow Diagram Outline: Biostimulant Activity of MSMs.

4. Bioprotectant Role and Mechanisms

Microbial secondary metabolites (MSMs) serve as potent bioprotectants by activating plant defense systems and directly suppressing pathogens. Their multifunctionality provides both direct and indirect protection against biotic stressors—including fungi, bacteria, viruses, and insect herbivores—making them indispensable components of integrated pest and disease management strategies (Ben Mrid et al., 2021; Nimbulkar et al., 2025). MSMs act through three primary mechanisms: induced systemic resistance, direct antimicrobial activity, and quorum sensing disruption.

4.1 Induced Systemic Resistance (ISR)

Induced Systemic Resistance (ISR) is a plant-wide immune response triggered by beneficial microbes and mediated by microbial metabolites; unlike Systemic Acquired Resistance (SAR), which is activated by pathogenic attack and involves salicylic acid (SA), ISR is primarily regulated through jasmonic acid (JA) and ethylene (ET) signaling pathways (Nimbulkar et al., 2025), with key metabolites such as pyocyanin, phenazines, and lipopeptides stimulating these pathways to activate defense-related genes, induce the production of pathogenesis-related (PR) proteins, and reinforce cell walls with lignin and callose deposition; for example, Pseudomonas fluorescens produces 2,4-diacetylphloroglucinol (DAPG), which primes the plant immune system without causing damage, thereby enabling faster and stronger responses upon pathogen attack and enhancing resistance against diverse pathogens such as Fusarium, Rhizoctonia, and Pythium species

(Ben Mrid et al., 2021); ISR is particularly valuable because it provides broad-spectrum protection without the metabolic costs associated with continuous defense activation, thereby maintaining plant growth and yield.

4.2 Antimicrobial Activity

Many microbial secondary metabolites (MSMs) exhibit direct antimicrobial properties by targeting pathogens through mechanisms such as membrane disruption, enzyme inhibition, and interference with metabolic pathways; for instance, lipopeptides like surfactin, iturin, and fengycin produced by Bacillus subtilis disrupt fungal cell membranes, inhibit spore germination, and prevent hyphal growth (Nimbulkar et al., 2025), phenolic compounds such as catechins and tannins inhibit microbial enzymes, reduce pathogen virulence, and act as antioxidants to protect plant tissues (Ben Mrid et al., 2021), while alkaloids including berberine and nicotine interfere with DNA replication and protein synthesis in pathogens, thereby reducing their ability to proliferate (Chakraborty & Chakraborty, 2024); these compounds often act synergistically, enhancing efficacy and lowering the risk of resistance development, and their broad-spectrum activity combined with natural origin makes them valuable tools for controlling soil-borne and foliar diseases within sustainable farming practices.

4.3 Quorum Sensing Disruption

Quorum sensing (QS) is a bacterial communication system that regulates virulence factor production, toxin secretion, and biofilm formation, and disrupting QS provides a non-lethal strategy to attenuate pathogen behavior while reducing selection pressure for resistance compared to conventional antimicrobials (Chakraborty & Chakraborty, 2024); certain microbial secondary metabolites (MSMs) achieve this by degrading or mimicking acyl-homoserine lactones (AHLs), the signaling molecules used in QS, with examples including AHL-lactonases produced by beneficial microbes that degrade AHLs to prevent signal transmission and phenazine derivatives from *Pseudomonas* spp. that interfere with QS signaling to block biofilm formation and toxin production, thereby neutralizing pathogens such as *Erwinia*, *Xanthomonas*, and *Agrobacterium* before infection occurs (Nimbulkar et al., 2025); by targeting communication rather than viability, QS interference represents a novel and sustainable approach to disease management, and together with immune priming (ISR) and direct antimicrobial activity, microbial secondary metabolites act as multifunctional bioprotectants that suppress pathogens, reduce reliance on synthetic pesticides, mitigate resistance development, and promote ecological balance, making their integration into crop protection strategies consistent with the goals of climate-smart and sustainable agriculture and offering long-term solutions for resilient farming systems.

5. Case Studies and Applications

Microbial secondary metabolites (MSMs) have demonstrated remarkable efficacy in real-world agricultural systems, functioning simultaneously as biostimulants and bioprotectants, and their dual roles in enhancing plant growth and suppressing pathogens make them valuable tools for integrated crop management; for example, *Bacillus subtilis*, one of the most extensively studied biocontrol agents, produces cyclic lipopeptides such as surfactin, fengycin, and iturin A that exhibit strong antifungal activity and act as elicitors of Induced Systemic Resistance (ISR), with surfactin disrupting fungal membranes and activating defense-related genes such as *PR1*, *LOX*, and *POD* to enhance resistance against *Botrytis cinerea* and *Penicillium digitatum* (Thonart et al., 2007; Valenzuela Ruiz et al., 2024), fengycin targeting filamentous fungi and stimulating the jasmonic acid pathway to increase defensive protein production, and field applications of strains such as *B. subtilis* GLB191 showing dual action by directly inhibiting grape downy mildew while stimulating plant immune responses, leading to their incorporation into commercial biopesticide formulations valued for broad-spectrum activity, environmental safety, and compatibility with organic farming systems; similarly, *Pseudomonas fluorescens*, a rhizobacterium, enhances plant growth and suppresses pathogens through the production of phenazine derivatives and pyocyanin, with phenazines exhibiting potent antifungal activity against *Fusarium oxysporum*, *Rhizoctonia solani*, and *Colletotrichum gloeosporioides* by disrupting fungal membranes and reducing spore viability (Lakshmikanthan et al., 2025), pyocyanin acting as a redox-active pigment that induces oxidative stress in pathogens and modulates iron metabolism to boost plant defense and microbial competitiveness (Abdelaziz et al., 2023), and these metabolites improving root colonization by altering microbial community dynamics, suppressing competing microbes, and enhancing nutrient uptake, so that applications such as seed treatments and soil amendments with *P. fluorescens* consistently improve crop yield, root health, and pathogen suppression, making this bacterium a cornerstone of biofertilizer and biocontrol technologies; likewise, *Trichoderma* spp., widely used fungal biocontrol agents, produce diverse secondary metabolites including peptaibols, polyketides, and 6-pentyl-α-pyrone (6-PP), with peptaibols acting as antimicrobial peptides that disrupt pathogen cell walls and membranes while also serving as signaling molecules that trigger ISR in host plants (Kaur et al., 2025), polyketides such as 6-PP exhibiting strong antifungal properties and promoting lateral root development in crops like *Arabidopsis thaliana*, and field applications of *Trichoderma*-based formulations successfully controlling soil-borne pathogens, improving plant vigor, and enhancing resilience under stress conditions, while beyond metabolite production *Trichoderma* contributes to mycoparasitism by directly competing with and parasitizing harmful fungi and simultaneously releasing growth-promoting hormones and enzymes, reinforcing its dual role as a biostimulant and bioprotectant; collectively, these case studies demonstrate the multifunctional nature of microbial metabolites, which act directly against pathogens through antimicrobial activity, prime plant immune systems via ISR, improve root architecture and nutrient uptake to enhance crop vigor, and contribute to ecological balance by fostering beneficial microbial communities, and commercial formulations based on *Bacillus*, *Pseudomonas*, and *Trichoderma* are increasingly integrated into sustainable crop management programs, reducing reliance on synthetic pesticides and fertilizers while improving long-term soil health (Table 2).

Table 2: Comparative Overview of Microbial Secondary Metabolites in Agriculture.

Microbe	Key Metabolites	Mechanisms of Action	Agricultural Applications
Bacillus subtilis	Surfactin, Fengycin, Iturin A	Disrupt fungal membranes Activate defense genes (*PR1*, *LOX*, *POD*) Stimulate jasmonic acid pathway	Control of grape downy mildew, *Botrytis cinerea*, *Penicillium digitatum* Commercial biopesticide formulations for broad-spectrum disease management
Pseudomonas fluorescens	Phenazines, Pyocyanin	Antifungal activity (membrane disruption, spore inhibition) Induce oxidative stress in pathogens Modulate iron metabolism Enhance root colonization	Seed treatments and soil amendments Suppression of *Fusarium*, *Rhizoctonia*, *Colletotrichum* Improved crop yield and root health
Trichoderma spp.	Peptaibols, Polyketides (e.g., 6-PP)	Disrupt pathogen cell walls and membranes Trigger ISR via signaling molecules Promote lateral root development Mycoparasitism against harmful fungi	Control of soil-borne pathogens Enhanced plant vigor under stress Widely used in biofungicide and biostimulant formulations

6. Challenges and Future Directions

A major challenge in the adoption of microbial secondary metabolites (MSMs) lies in the lack of standardized formulations, as these compounds are often produced in variable quantities depending on microbial strain, growth conditions, substrate availability, and fermentation parameters, which complicates the development of consistent, shelf-stable products; moreover, the complexity of metabolite mixtures makes it difficult to isolate, quantify, and stabilize active ingredients, a process crucial for dosage optimization, reproducibility, and regulatory approval (Marks et al., 2025), and while analytical advances such as LC-MS/MS, NMR spectroscopy, and metabolomic fingerprinting can help identify and quantify key metabolites to enable precise formulation and quality control (Nimbulkar et al., 2025), bioprocess optimization through standardized fermentation protocols, scaled bioreactors, and genetically engineered microbial strains may improve yield consistency, and encapsulation technologies such as nano-encapsulation, polymer matrices, and biochar carriers can enhance metabolite stability, prolong shelf life, and ensure controlled release in field conditions; however, the regulatory landscape for biostimulants and bioprotectants remains fragmented and often lacks clear guidelines for MSM-based products, since unlike synthetic agrochemicals these biologically derived compounds may fall under overlapping categories such as biofertilizers, biopesticides, or microbial inoculants, leading to confusion, delays in approval, and limited commercialization (Marks et al., 2025), and thus harmonization of international regulatory frameworks is needed to reduce ambiguity and accelerate market entry, while establishing dedicated MSM guidelines will encourage innovation and investment, and collaborative governance involving academia, industry stakeholders, and regulatory bodies is essential to streamline approval processes, ensure safety standards, and build farmer confidence; furthermore, although laboratory and greenhouse trials often demonstrate strong efficacy, field-level performance can be inconsistent due to environmental variability, soil microbiome interactions, and crop-specific responses, with factors such as temperature, pH, moisture, and native microbial communities influencing metabolite stability and activity (Nimbulkar et al., 2025), and therefore site-specific formulations tailored to local soil and climate conditions, multi-location and multi-season trials across diverse agroecological zones, and delivery technologies such as encapsulation, controlled-release carriers, and co-formulation with compatible microbes are needed to improve consistency and persistence in the field (Marks et al., 2025); to overcome these challenges and unlock the full potential of MSMs, future research should prioritize high-throughput metabolomic profiling and systems biology approaches to unravel the complexity of MSM production, identify novel bioactive compounds, and optimize fermentation conditions (Nimbulkar et al., 2025), synergistic formulations that combine multiple metabolites or microbial strains to yield enhanced biostimulant and bioprotectant functions (Marks et al., 2025), integration with precision agriculture tools such as remote sensing, soil sensors, drones, and AI-driven analytics to guide targeted application of MSMs for improved efficiency and reduced waste, synthetic biology and genetic engineering to develop microbial strains capable of overproducing specific metabolites or novel analogs for greater efficacy and scalability, and farmer-centric approaches including training programs, demonstration plots, and participatory research to accelerate adoption and ensure technologies are tailored to local practices; ultimately, the future of MSMs in agriculture depends on overcoming challenges related to formulation standardization, regulatory clarity, and field-level consistency, and advances in analytical chemistry, biotechnology, and precision agriculture will be pivotal in addressing these barriers, enabling the integration of MSMs into holistic crop management systems that support resilient, resource-efficient, and ecologically balanced practices aligned with global food security and sustainability goals.

7. CONCLUSION

Microbial secondary metabolites (MSMs) represent a transformative frontier in sustainable agriculture, offering potent and eco-compatible alternatives to conventional synthetic agrochemicals. Produced by diverse microbial taxa under specific environmental or developmental conditions, these bioactive compounds exhibit dual functionality that is both agronomically and ecologically significant (Marks et al., 2025; Nimbulkar et al., 2025).

As biostimulants, MSMs enhance plant growth, nutrient uptake, and stress tolerance by modulating endogenous hormonal pathways and fostering beneficial plant–microbe interactions (Ben Mrid et al., 2021). As bioprotectants, they fortify plant defense systems and suppress a wide range of pathogens through antimicrobial activity, immune priming, and quorum sensing disruption (Chakraborty & Chakraborty, 2024). This multifunctionality positions MSMs as integral components of next-generation crop management strategies that prioritize productivity, resilience, and ecological balance.

The integration of MSMs into agricultural practices aligns with the global imperative to reduce chemical inputs, restore soil health, and mitigate environmental footprints (Marks et al., 2025). Their specificity, low toxicity, and compatibility with natural ecosystems make them ideal candidates for bioformulations that support climate-resilient farming systems.

Importantly, their adaptability across diverse agroclimatic zones underscores their potential to serve as universal tools in addressing food security challenges (Nimbulkar et al., 2025).

Nevertheless, realizing their full potential requires overcoming persistent challenges—particularly in formulation standardization, regulatory clarity, and field-level consistency. Advances in metabolomics, synthetic biology, and precision agriculture will be instrumental in unlocking new applications, improving efficacy, and ensuring scalability (Marks et al., 2025; Elshafie et al., 2023). Furthermore, interdisciplinary collaboration among microbiologists, agronomists, biotechnologists, and policymakers will be critical to accelerate innovation and adoption.

Looking ahead, the discovery of novel metabolites, exploration of synergistic interactions, and integration with digital agriculture platforms will expand the scope of MSMs beyond traditional biostimulant and bioprotectant roles. They are poised to become cornerstones of a new paradigm in agriculture—one that is productive, resilient, and ecologically harmonious.

In essence, microbial secondary metabolites are not merely supplements to conventional practices but catalysts for a new green revolution—where biological intelligence replaces chemical dependence, and sustainability becomes the cornerstone of global food security (Ben Mrid et al., 2021). Their promise lies not only in enhancing crop performance but also in reshaping agriculture into a system that harmonizes productivity with planetary health.

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