



Paper Type: Original Article

Biocompounds in Soil Health and Sustainable Agriculture: Molecular Interactions, Microbial Processes, and Environmental Implications

Zakiyeh Safa* 

Department of Agricultural Engineering, Islamic Azad University, Rasht Branch, Rasht, Iran; zakiesafa63@gmail.com.

Citation:

Received: 09 December 2025

Revised: 13 February 2026

Accepted: 27 April 2026

Safa, Z. (2026). Biocompounds in soil health and sustainable agriculture: Molecular interactions, microbial processes, and environmental implications. *Biocompounds*, 3(4), 284-313.

Abstract

Biocompounds are important chemical mediators within soil-plant-microbe systems and play diverse roles in soil biological processes, nutrient cycling, and plant adaptation to environmental stress. Their presence in soil originates from multiple sources, including plant roots, plant residues, and microbial metabolism, resulting in a chemically diverse mixture of phenolics, flavonoids, organic acids, amino acids, peptides, polysaccharides, terpenoids, siderophores, phytohormones, and microbial secondary metabolites. This review examines the roles of biocompounds in soil health and sustainable agriculture, with particular emphasis on their molecular interactions, microbial processes, environmental fate, and ecological implications. The discussion highlights interactions of biocompounds with plant roots, soil minerals, organic matter, and metals, as well as their effects on microbial community structure, metabolic activity, nutrient transformation, and soil organic matter dynamics. Their potential contribution to plant adaptation under drought, salinity, temperature, oxidative, and nutrient stresses is also considered. Particular attention is given to adsorption, degradation, transformation, persistence, bioavailability, and potential effects on non-target organisms, which collectively determine the environmental behavior of biocompounds. Emerging approaches based on metabolomics, multi-omics, spatial analysis, microbiome engineering, Artificial Intelligence (AI), and precision agriculture offer new opportunities to investigate these complex interactions and develop more predictive approaches to soil management. Nevertheless, challenges remain in understanding compound mixtures, transformation products, field-scale variability, and long-term ecological effects. Integrating molecular, microbial, physicochemical, and field-scale approaches will be essential for translating knowledge of biocompounds into environmentally responsible strategies for maintaining soil health and supporting sustainable agricultural systems.

Keywords: Biocompounds, Soil health, Sustainable agriculture, Rhizosphere, Soil microbiome, Bioavailability, Multi-omics.

1 | Introduction

Soil is a fundamental component of terrestrial ecosystems and agricultural production, providing physical support for plants while serving as a dynamic reservoir of nutrients, organic matter, microorganisms, and diverse chemical compounds. Beyond its role as a substrate for plant growth, soil functions as a complex

 Corresponding Author: zakiesafa63@gmail.com

 <https://doi.org/10.48313/bic.vi.83>



Licensee System Analytics. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0>).

biological system in which physical, chemical, and biological processes interact continuously [1–3]. The productivity, stability, and resilience of agricultural systems therefore depend not only on the availability of essential nutrients but also on preserving soil structure, organic matter, microbial diversity, nutrient cycling, and ecological functions. However, intensive agricultural practices, excessive use of synthetic fertilizers and pesticides, soil erosion, salinization, depletion of organic matter, and increasing environmental stresses have contributed to soil degradation and reduced the sustainability of agricultural systems. These challenges have increased interest in biological approaches that can improve soil functions while reducing dependence on conventional chemical inputs [1–8].

Soil health has emerged as an important framework for evaluating soil's capacity to sustain plant productivity, maintain biodiversity, regulate nutrient and carbon cycling, and support ecosystem functions over time. Soil health is governed by the combined performance of physical, chemical, and biological properties rather than by a single measurable characteristic. Among these components, soil microorganisms play a central role because they participate in organic matter decomposition, nutrient transformation, carbon cycling, mineralization, and interactions with plant roots. The rhizosphere, which represents the soil region directly influenced by plant roots, is particularly dynamic because it constitutes an interface where plants, microorganisms, minerals, water, and organic molecules interact [9–11]. Consequently, understanding the chemical and biological processes occurring within the rhizosphere is essential for developing approaches aimed at improving soil health and agricultural sustainability.

Within this complex environment, biocompounds represent a diverse group of biologically derived molecules that can influence soil, plants, and microorganisms. Depending on their biological origin, these compounds may include phenolic compounds, flavonoids, organic acids, amino acids, peptides, polysaccharides, terpenoids, alkaloids, lipids, phytohormones, siderophores, and a wide range of microbial metabolites. Biocompounds can originate from plants, microorganisms, decomposing organic matter, or interactions among organisms within the soil ecosystem. Their importance extends beyond direct biological activity; many also function as signaling molecules, nutrient-mobilizing agents, chemical mediators, or regulators of microbial interactions. Thus, biocompounds can contribute to the establishment and regulation of complex communication networks between plants and microorganisms in the soil environment [12].

Plant roots continuously release a variety of organic compounds into the rhizosphere through root exudation, mucilage production, and turnover of root tissues. These compounds include sugars, amino acids, organic acids, phenolic compounds, flavonoids, and other specialized metabolites. Root-derived biocompounds can serve as carbon and energy sources for microorganisms, influence microbial recruitment, modify nutrient availability, and participate in chemical signaling. In turn, microorganisms can transform these compounds or produce their own metabolites, which may subsequently affect root development, plant nutrition, and stress responses. This reciprocal relationship creates a dynamic molecular network in which plants influence microbial communities through chemical signals, whereas microorganisms modify plant performance through metabolites, nutrients, hormones, and other signaling mechanisms. Therefore, biocompounds represent important molecular mediators of plant–soil–microbe interactions [13–16].

The biological behavior of a biocompound in soil depends strongly on its chemical structure and on the physicochemical and biological characteristics of the surrounding environment. Following their release or application, biocompounds may undergo adsorption to soil minerals, complexation with metal ions, microbial transformation, degradation, oxidation, or incorporation into soil organic matter. These processes determine their persistence, mobility, bioavailability, and biological effects. Importantly, microbial transformation may generate products with biological properties that differ from those of the original compound. Consequently, evaluating the role of biocompounds in soil requires consideration of both their intrinsic biological activity and their environmental fate [17].

Soil microorganisms are major drivers of the transformation and biological activity of biocompounds. Bacteria, fungi, archaea, and other microbial groups possess diverse metabolic capacities that enable them to degrade, transform, synthesize, and utilize a broad range of organic molecules. Beneficial microorganisms,

including plant-growth-promoting rhizobacteria, mycorrhizal fungi, and other functional members of the soil microbiome, can produce metabolites involved in nutrient acquisition, plant growth regulation, stress tolerance, and biological interactions. Processes such as biological nitrogen fixation, phosphate solubilization, siderophore production, organic matter decomposition, phytohormone synthesis, and microbial antagonism are closely associated with the functional activity of soil microbial communities. At the same time, biocompounds released by plants or microorganisms can influence microbial abundance, diversity, community structure, and metabolic activity. This bidirectional relationship highlights the importance of considering biocompounds and soil microorganisms as interconnected components of the same ecological system [18].

The significance of these interactions becomes particularly apparent under environmental stresses that increasingly threaten agricultural productivity. Drought, salinity, temperature extremes, nutrient imbalance, and soil contamination can alter root exudation, microbial community composition, nutrient availability, and the transformation of organic compounds. Plants and microorganisms respond to these conditions by modifying their metabolic profiles and producing compounds associated with antioxidant protection, osmotic regulation, signaling, nutrient acquisition, and defense. Biocompounds may therefore contribute to plant adaptation by influencing root–microbe interactions and regulating biological processes within the rhizosphere. Such interactions may improve nutrient-use efficiency, support microbial functioning, and contribute to greater resilience of agricultural ecosystems under unfavorable environmental conditions [19].

The potential contribution of biocompounds to sustainable agriculture is closely related to their ability to support biological soil functions rather than simply provide direct inputs to plants. By modulating microbial activity, nutrient transformations, root development, and plant responses to environmental stress, biocompounds may help improve the efficiency of naturally occurring soil processes. This perspective is particularly relevant in agricultural systems where excessive dependence on synthetic fertilizers and pesticides can contribute to nutrient losses, disruption of soil microbial communities, contamination of soil and water resources, and long-term degradation of soil quality. Biologically based strategies that enhance endogenous soil processes may therefore complement conventional agricultural management and contribute to more resource-efficient production systems. Nevertheless, the effects of biocompounds are highly context-dependent and can vary according to soil characteristics, climate, crop genotype, microbial community composition, compound concentration, and application method [20].

Despite increasing knowledge of plant–soil–microbe interactions, important questions remain regarding the mechanisms through which individual biocompounds and complex mixtures influence soil health and microbial processes. A compound that exhibits strong biological activity under controlled laboratory conditions may behave differently in agricultural soils because of adsorption, degradation, limited bioavailability, or interactions with other soil constituents. Similarly, a biocompound's effects on microbial communities may depend on existing ecological conditions and change over time. Translating laboratory findings into consistent field-scale outcomes therefore remains a major challenge. A mechanistic understanding of these interactions is essential for determining when and how biocompounds can provide reliable benefits without causing unintended ecological effects [11].

Recent advances in high-throughput sequencing, metabolomics, transcriptomics, proteomics, and bioinformatics have created new opportunities to investigate these complex relationships at molecular and community levels. Integrating multi-omics data with soil chemistry, microbial ecology, and plant physiology can help identify relationships between specific biocompounds, microbial functions, and plant responses. Such approaches may contribute to the development of more targeted, context-specific strategies for managing soil biological functions. In parallel, increasing attention to microbiome engineering and precision biological inputs provides opportunities to manipulate beneficial interactions within the rhizosphere while reducing unnecessary external inputs.

Despite these advances, a comprehensive understanding of how biocompounds connect molecular interactions, microbial processes, soil health, and environmental sustainability remains limited. Many studies

have focused on individual compounds, specific microbial groups, or particular plant responses, whereas the interconnected nature of these processes requires a broader systems-level perspective. In addition, the environmental fate, persistence, transformation, and ecological consequences of biocompounds require further consideration when assessing their suitability for sustainable agricultural applications [21–26].

Accordingly, this review examines the role of biocompounds in soil health and sustainable agriculture, with particular emphasis on their molecular interactions, influence on soil microbial processes, and broader environmental implications. The review first discusses the major sources and classes of biocompounds relevant to soil systems and then explores their interactions with plant roots, soil microorganisms, and soil components. Particular attention is given to their effects on microbial functions, nutrient cycling, soil biological quality, and plant responses to environmental stress. The environmental fate, potential benefits, limitations, and ecological considerations associated with biocompound-based strategies are also discussed. Finally, emerging approaches, including multi-omics, microbiome-oriented strategies, and precision biological inputs, are considered as potential directions for advancing the role of biocompounds in sustainable and resilient agricultural systems.

2 | Biocompounds in Soil Systems: Sources, Classes, and Characteristics

Biocompounds present in soil systems originate from diverse biological sources and represent a chemically and functionally heterogeneous group of molecules. Their presence may result from natural plant metabolism, root exudation, microbial biosynthesis, decomposition of plant and animal residues, or biological transformations occurring within the soil environment. In agricultural ecosystems, additional sources may include organic amendments, composts, microbial inoculants, plant-derived materials, and other biologically based inputs. The concentration and composition of these compounds are highly dynamic and can vary according to plant species, developmental stage, soil properties, climatic conditions, microbial community structure, and agricultural management practices. Consequently, the soil environment contains a continuously changing mixture of biocompounds rather than a fixed chemical composition [14].

2.1 | Plant-Derived Biocompounds

Plants are among the major sources of biologically active compounds entering soil systems. A substantial proportion of plant-derived molecules reaches the rhizosphere through root exudation, secretion, cell turnover, and decomposition of plant residues. Root exudates contain a complex mixture of primary and secondary metabolites, including sugars, amino acids, organic acids, phenolic compounds, flavonoids, terpenoids, and other specialized metabolites. These compounds can influence the chemical properties of the rhizosphere and provide substrates or signals that shape microbial community structure and activity.

Primary metabolites released by roots, particularly carbohydrates and amino acids, can provide readily available sources of carbon and nitrogen for soil microorganisms. Organic acids, including citrate, malate, oxalate, and related compounds, can modify the local chemical environment and participate in the mobilization of mineral nutrients. In contrast, secondary metabolites such as phenolics, flavonoids, terpenoids, and other specialized compounds may have more specific ecological functions, including chemical signaling, microbial recruitment, defense, and regulation of plant–microbe interactions. The composition of root-derived compounds is therefore closely associated with plant nutritional status, developmental stage, genotype, and environmental conditions [18–27].

Plant residues represent another major source of biocompounds in soil. Following senescence and decomposition, complex plant molecules are progressively transformed by soil microorganisms and extracellular enzymes. During this process, soluble metabolites and intermediate products are released into the soil, where they can serve as substrates for microbial metabolism or participate in chemical interactions with minerals and soil organic matter. The decomposition of plant residues therefore represents an important

pathway through which plant-derived biocompounds contribute to nutrient cycling and the formation of soil organic matter.

2.2 | Microbial-Derived Biocompounds

Soil microorganisms are not only consumers and transformers of biocompounds but also important producers of biologically active molecules. Bacteria, fungi, archaea, and other microorganisms synthesize a broad spectrum of metabolites as part of their growth, communication, competition, adaptation, and interactions with plants and other microorganisms. These compounds include antibiotics, siderophores, organic acids, volatile organic compounds, peptides, enzymes, signaling molecules, and hormone-like substances.

Microbial-derived compounds can influence soil processes at multiple levels. For example, siderophores can bind iron and modify its availability in the rhizosphere, while microbial organic acids may contribute to nutrient mobilization. Certain microbial metabolites can influence root development or plant defense responses, whereas others can suppress competing microorganisms or soil-borne pathogens. Microbial metabolites can also contribute to the establishment of specific microbial associations by serving as signaling molecules or substrates for other members of the soil community [27].

The production of microbial biocompounds is strongly influenced by environmental conditions. Carbon availability, nutrient status, pH, moisture, temperature, oxygen availability, and interactions with other microorganisms can all affect microbial metabolic activity. Therefore, the biological functions of microbial-derived compounds should be considered within the ecological context in which they are produced rather than as isolated molecular effects.

2.3 | Major Chemical Classes of Biocompounds

Biocompounds occurring in soil can be broadly classified by their chemical structures, biological origins, and functional roles. Although considerable overlap exists among these categories, such classification provides a useful framework for understanding their environmental behavior and biological functions, as summarized in *Table 1*.

Phenolic compounds and flavonoids constitute an important group of plant-derived secondary metabolites. Their chemical structures allow them to participate in redox reactions, metal interactions, and molecular recognition. In the rhizosphere, phenolic compounds can influence microbial activity and community composition, while flavonoids may participate in plant-microbe signaling. Their persistence and activity depend on molecular structure, soil pH, microbial transformation, and interactions with soil minerals and organic matter [26].

Organic acids are another important class of biocompounds in soil systems. Compounds such as citrate, malate, acetate, and oxalate can alter local pH, interact with mineral surfaces, and influence the solubility and mobility of nutrients and metals. Through these mechanisms, organic acids can contribute to nutrient mobilization and modify the chemical environment surrounding plant roots.

Amino acids, peptides, and proteins can originate from root exudates, microbial activity, and decomposition of organic residues. Amino acids can serve as readily available sources of carbon and nitrogen for microorganisms and may also participate in signaling processes. Microbial peptides and proteins can have more specialized functions, including antimicrobial activity, signaling, and regulation of microbial interactions [21].

Polysaccharides and other complex carbohydrates are important components of root mucilage, microbial extracellular polymeric substances, and decomposing organic residues. These compounds can influence soil aggregation, water retention, microbial attachment, and the formation of microscale habitats. Microbial extracellular polymers are particularly relevant to soil structure because they can contribute to the stabilization of soil particles and the development of microbial biofilms.

Terpenoids, alkaloids, and other specialized metabolites represent structurally diverse groups with a wide range of ecological functions. Depending on their chemical properties, these compounds may participate in plant defense, microbial interactions, signaling, or adaptation to environmental stress. Their concentrations in soil are often relatively low compared with major primary metabolites, but their biological effects can nevertheless be significant because many act at signaling or regulatory levels.

2.4 | Factors Governing the Occurrence and Stability of Biocompounds

The presence and biological activity of biocompounds in soil are controlled by interactions among their chemical properties and environmental conditions. Soil pH, texture, organic matter content, mineral composition, moisture, temperature, and redox status can influence the adsorption, degradation, mobility, and bioavailability of individual compounds. Clay minerals and soil organic matter, for example, can interact with organic molecules and affect their persistence and availability to microorganisms and plant roots [28–32].

Microbial activity represents another major determinant of biocompound dynamics. Many soil microorganisms possess enzymatic systems capable of transforming complex organic molecules into simpler metabolites. Such transformations can either reduce the activity of the original compound or generate new molecules with distinct biological properties. Consequently, the environmental behavior of a biocompound cannot be predicted solely from its chemical structure; its interactions with the soil matrix and resident microbial community must also be considered [31].

Environmental conditions can further modify these processes. Changes in temperature and soil moisture influence microbial metabolism and enzymatic activity, while drought and salinity can alter both the quantity of compounds released by roots and their subsequent transformation in the rhizosphere. Agricultural practices, including irrigation, fertilization, crop rotation, residue management, and organic amendments, can also modify the abundance and composition of biocompounds indirectly by altering plant physiology and microbial community structure.

2.5 | Functional Significance of Biocompounds in Soil

The ecological importance of biocompounds arises from their ability to connect chemical, biological, and physical processes within soil ecosystems. Rather than acting as isolated substances, these molecules participate in interconnected networks involving plants, microorganisms, minerals, and organic matter. Their functions may include providing metabolic substrates, mediating chemical communication, modifying nutrient availability, regulating microbial interactions, influencing root development, and contributing to plant adaptation to environmental stress.

This multifunctionality makes biocompounds particularly relevant to soil health and sustainable agriculture. However, their effects are strongly dependent on concentration, chemical structure, environmental conditions, and interactions with other components of the soil ecosystem. A comprehensive assessment therefore requires integrating chemical, microbiological, and ecological perspectives rather than evaluating individual compounds alone [32].

Table 1. Major classes, sources, representative examples, and functional roles of biocompounds in soil systems.

Major Class of Biocompounds	Major Sources	Representative Examples	Major Functions in Soil Systems
Phenolic compounds	Plant roots, plant residues, microbial metabolism	Phenolic acids, tannins	Chemical signaling, microbial modulation, antioxidant activity, interactions with soil minerals
Flavonoids	Root exudates, plant residues	Quercetin, kaempferol, naringenin	Plant–microbe signaling, microbial recruitment, regulation of rhizosphere interactions
Organic acids	Root exudates, microbial metabolism, decomposition	Citrate, malate, oxalate, acetate	Nutrient mobilization, pH modification, metal complexation, microbial substrates

Table 1. Continued.

Major Class of Biocompounds	Major Sources	Representative Examples	Major Functions in Soil Systems
Amino acids	Root exudates, microbial biomass, decomposition	Glutamate, glutamine, alanine	Carbon and nitrogen sources, microbial metabolism, signaling
Peptides and proteins	Microorganisms, roots, decomposing residues	Antimicrobial peptides, extracellular enzymes	Microbial interactions, nutrient transformation, biological regulation
Polysaccharides	Root mucilage, microbial extracellular polymers, plant residues	Cellulose, pectins, extracellular polysaccharides	Soil aggregation, water retention, microbial adhesion, structural stabilization
Terpenoids	Plant roots, plant residues, microorganisms	Terpenes, diterpenes, sesquiterpenes	Chemical signaling, plant defense, microbial interactions
Alkaloids	Plant roots and residues, microorganisms	Nicotine, caffeine, quinolizidine alkaloids	Plant defense, microbial regulation, ecological interactions
Siderophores	Soil bacteria and fungi	Enterobactin, pyoverdine, desferrioxamine	Iron chelation, nutrient acquisition, microbial competition
Phytohormones and hormone-like compounds	Plants, rhizosphere microorganisms	Auxins, cytokinins, gibberellins, abscisic acid	Root development, plant growth regulation, stress responses
Microbial secondary metabolites	Bacteria, fungi, actinomycetes	Antibiotics, volatile organic compounds, signaling metabolites	Microbial communication, competition, pathogen suppression, plant responses

3 | Molecular Interactions of Biocompounds at the Soil-Plant Interface

The soil-plant interface represents a highly dynamic microenvironment in which biocompounds participate in continuous chemical interactions among plant roots, soil minerals, organic matter, and microorganisms. The biological functions of biocompounds in this environment are determined not only by their intrinsic chemical properties but also by their ability to interact with surrounding biological and abiotic components. These interactions influence the mobility, persistence, bioavailability, and biological activity of biocompounds and consequently affect nutrient availability, root development, microbial colonization, and plant responses to environmental conditions. Understanding these molecular interactions is therefore essential for explaining how biocompounds contribute to soil health and sustainable agricultural systems [31].

3.1 | Interactions with Plant Roots and Root Exudates

Plant roots constitute a major biological interface through which biocompounds enter and influence the soil environment. Root exudation releases a diverse mixture of low- and high-molecular-weight compounds into the rhizosphere, including sugars, amino acids, organic acids, phenolics, flavonoids, terpenoids, and signaling molecules. The composition of root exudates varies according to plant species and genotype as well as developmental stage, nutritional status, and environmental stress. These compounds can modify the chemical

characteristics of the rhizosphere and establish molecular signals that influence both plant and microbial processes [33].

Biocompounds released from roots can affect root architecture and physiological activity through direct and indirect mechanisms. Certain organic acids can modify the availability of nutrients and minerals near root surfaces, whereas signaling compounds can influence root-associated microbial communities. Phenolic compounds and flavonoids, for example, may participate in selective microbial recruitment and communication, thereby contributing to the establishment of specific rhizosphere associations. Conversely, microbial metabolites can modify root development and root exudation patterns, creating feedback mechanisms between plant metabolism and microbial activity [34].

The interaction between root-derived biocompounds and the rhizosphere is therefore dynamic rather than unidirectional. Changes in nutrient availability, microbial colonization, and environmental stress can alter the composition of root exudates, while changes in the surrounding microbial community can subsequently modify the quantity and composition of compounds released by the plant. This feedback contributes to the development of a chemically and biologically distinct rhizosphere environment.

3.2 | Interactions with Soil Minerals and Clay Surfaces

Following their release into soil, biocompounds can interact with mineral surfaces through adsorption, ion exchange, hydrogen bonding, electrostatic interactions, and other physicochemical mechanisms. Clay minerals and metal oxides are particularly important because of their high surface area and reactive functional groups. These interactions can influence the mobility and persistence of organic molecules and determine whether a compound remains available for uptake or microbial transformation.

Organic acids and phenolic compounds are particularly relevant in this context. Their functional groups can interact with mineral surfaces and metal ions, potentially modifying the solubility and mobility of nutrients and trace elements. Complexation with metal ions can also alter the chemical form and bioavailability of both the biocompound and the associated mineral component. Such interactions may contribute to nutrient mobilization in the rhizosphere but can also influence the retention and persistence of organic molecules within the soil matrix [35].

The extent of mineral–biocompound interactions depends on soil pH, mineral composition, ionic strength, organic matter content, and molecular structure. Compounds containing carboxyl, hydroxyl, amino, or other reactive functional groups may exhibit different affinities toward mineral surfaces. Consequently, the same biocompound may display substantially different mobility and bioavailability in different soil types.

3.3 | Interactions with Soil Organic Matter

Soil organic matter represents another major component controlling the environmental behavior of biocompounds. Organic molecules can associate with humic substances and other components of soil organic matter through hydrogen bonding, hydrophobic interactions, electrostatic forces, and covalent or non-covalent associations. These interactions can affect the retention, stabilization, and subsequent transformation of biocompounds [26–32].

Association with soil organic matter may protect certain compounds from rapid degradation and thereby increase their persistence in soil. Conversely, strong binding may decrease their immediate bioavailability to microorganisms or plant roots. The balance between stabilization and bioavailability is therefore an important determinant of the functional effects of biocompounds in soil. In addition, the incorporation of biologically derived molecules into soil organic matter can contribute to the formation and transformation of organic carbon pools.

The relationship between biocompounds and soil organic matter is particularly relevant to long-term soil health. Biocompounds derived from root residues and microbial metabolism may serve as precursors for more complex organic matter structures, while microbial transformation can generate metabolites that

become incorporated into stable soil organic matter fractions. Thus, molecular interactions between biocompounds and organic matter can link short-term biological activity with longer-term soil carbon dynamics.

3.4 | Biocompound-Metal Interactions

Metal ions represent important chemical partners for many biocompounds in soil. Molecules containing hydroxyl, carboxyl, amino, or other functional groups can bind metal ions through complexation or chelation. Such interactions may modify the solubility, mobility, and biological availability of metals and nutrients. This process can have both beneficial and undesirable consequences depending on the specific metal, compound, concentration, and environmental conditions.

For essential micronutrients such as iron, zinc, manganese, and copper, complexation can influence nutrient availability to plants and microorganisms. Siderophores produced by microorganisms are particularly specialized examples of metal-binding biocompounds. Their high affinity for iron allows microorganisms to acquire this essential element under conditions where its bioavailability is limited. Other plant- and microbe-derived compounds may similarly influence metal mobility and nutrient acquisition through weaker but ecologically relevant interactions [36].

Biocompounds can also interact with potentially toxic metals such as cadmium, lead, chromium, and mercury. Complexation, adsorption, or transformation processes may alter metal mobility and bioavailability and consequently influence their uptake by plants and microorganisms. Therefore, understanding biocompound-metal interactions is important not only for nutrient management but also for evaluating the potential role of biological molecules in soils affected by metal contamination.

3.5 | Molecular Signaling between Plants and Microorganisms

One of the most biologically significant functions of biocompounds in the rhizosphere is their role in molecular communication. Plants release specific molecules that can act as chemical signals for microorganisms, while microorganisms produce metabolites that influence plant signaling pathways. This chemical communication contributes to the establishment of beneficial associations and can influence root development, nutrient acquisition, and plant defense.

Flavonoids and other specialized plant metabolites can serve as recognition signals for certain microorganisms, while microbial compounds such as phytohormones, volatile organic compounds, siderophores, and signaling metabolites can alter plant physiological responses. These interactions can influence root architecture and create favorable conditions for microbial colonization. In beneficial plant-microbe associations, molecular signaling may therefore contribute to the establishment of feedback mechanisms that improve nutrient acquisition and plant adaptation to environmental stress.

Importantly, molecular signaling is not restricted to interactions between a plant and a single microbial species. The rhizosphere contains diverse microbial communities in which signaling molecules can influence multiple organisms simultaneously. Consequently, the effects of a particular biocompound may depend on the composition and functional characteristics of the surrounding microbial community [37].

3.6 | Effects on Biocompound Bioavailability and Environmental Fate

The biological activity of a biocompound depends strongly on its bioavailability. A molecule may possess considerable biological activity in solution but exhibit limited effects in soil if it becomes strongly adsorbed to mineral surfaces or incorporated into soil organic matter. Conversely, weakly retained compounds may remain highly mobile and accessible to microorganisms and plant roots but may also undergo rapid degradation or leaching.

Bioavailability is therefore determined by the balance between adsorption, desorption, degradation, transformation, diffusion, and biological uptake. Soil pH, moisture, temperature, organic matter, mineral

composition, and microbial activity all contribute to this balance. In addition, molecular characteristics such as polarity, charge, molecular size, and functional groups influence how a biocompound interacts with the soil matrix.

These processes demonstrate why the biological effects of biocompounds cannot be predicted solely from laboratory measurements of their intrinsic activity. Their behavior within the complex soil matrix must also be considered. Understanding the relationship between molecular structure, soil interactions, bioavailability, and biological activity is consequently important for the rational development of biocompound-based approaches for sustainable agriculture [32].

3.7 | Integrated Perspective on Molecular Interactions

Biocompounds function within a complex molecular network connecting plant roots, microorganisms, soil minerals, and organic matter. The major molecular interactions occurring at the soil-plant interface and their potential consequences for soil and plant processes are summarized in *Table 2*. The major molecular interactions occurring at the soil-plant interface and their potential consequences for soil and plant processes are summarized in *Table 2* and schematically illustrated in *Fig. 1*.

Their effects may arise from direct chemical interactions, molecular signaling, modification of nutrient availability, or changes in the physicochemical environment surrounding roots. Importantly, these mechanisms frequently occur simultaneously and may influence one another. For example, a root-derived organic acid may alter mineral solubility, modify nutrient availability, influence microbial activity, and subsequently change the composition of microbial metabolites in the rhizosphere.

This interconnected nature highlights the need to move beyond studying individual biocompounds or isolated interactions and toward an integrated understanding of the soil-plant-microbe system. Such a perspective is particularly relevant for sustainable agriculture because the long-term effectiveness of biocompound-based strategies depends on their compatibility with soil properties, microbial communities, plant physiology, and environmental conditions [38].

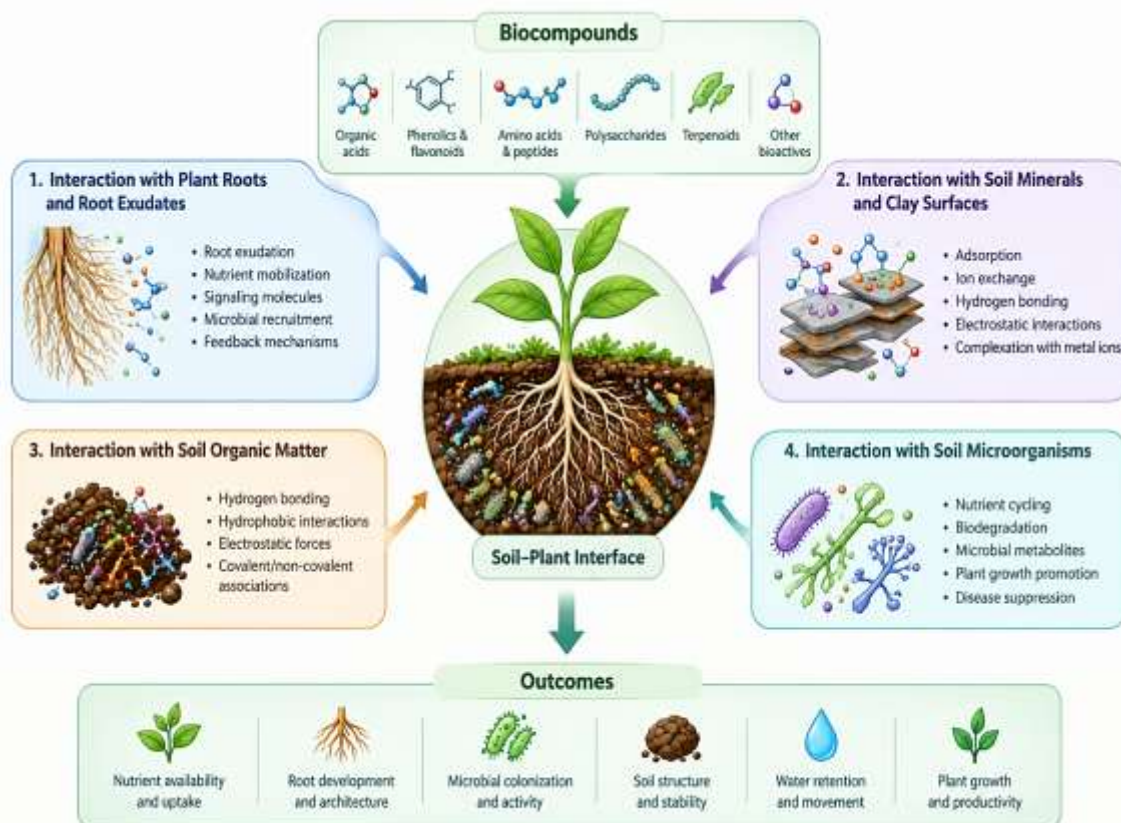


Fig. 1. Major interactions of biocompounds at the soil-plant interface and their associated outcomes.**Table 2. Major molecular interactions of biocompounds at the soil-plant interface and their potential consequences for**

Molecular Interaction	Major Biocompounds Involved	Main Interacting Components	Potential Consequences
Root–biocompound interactions	Organic acids, flavonoids, phenolics, amino acids	Plant roots and root exudates	Modulation of root development, nutrient acquisition, and rhizosphere chemistry
Mineral adsorption and desorption	Phenolics, organic acids, polysaccharides	Clay minerals, metal oxides	Changes in compound mobility, persistence, and bioavailability

Table 2. Continued.

Molecular Interaction	Major Biocompounds Involved	Main Interacting Components	Potential Consequences
Organic matter association	Phenolics, polysaccharides, proteins, microbial metabolites	Humic substances and soil organic matter	Compound stabilization, carbon transformation, and altered bioavailability
Metal complexation	Organic acids, phenolics, siderophores	Fe, Zn, Mn, Cu and potentially toxic metals	Modification of metal mobility, solubility, and nutrient availability
Plant–microbe signaling	Flavonoids, phytohormones, volatile compounds	Plant roots and rhizosphere microorganisms	Microbial recruitment, root colonization, plant growth, and defense responses
Microbe–microbe signaling	Microbial metabolites, peptides, volatile compounds	Bacterial and fungal communities	Microbial communication, competition, cooperation, and community assembly
Biocompound transformation	Organic acids, phenolics, terpenoids, carbohydrates	Soil microorganisms and extracellular enzymes	Formation of transformation products and changes in biological activity
Biocompound–soil matrix interactions	Various biocompounds	Soil minerals, organic matter, water phase	Regulation of mobility, degradation, persistence, and bioavailability

4 | Biocompounds and Soil Microbial Processes

Soil microorganisms are major drivers of nutrient transformation, organic matter decomposition, plant–microbe interactions, and maintenance of soil functional stability. Bacteria, fungi, archaea, and other microorganisms continuously interact with biocompounds originating from plant roots, microbial metabolism, and decomposing organic residues. These interactions can modify microbial community composition, metabolic activity, enzyme production, nutrient availability, and interspecific relationships within the soil environment. Consequently, biocompounds are not merely substrates or secondary products of microbial activity but can act as chemical mediators that influence the organization and functioning of soil microbial communities [24].

4.1 | Regulation of Soil Microbial Diversity and Community Structure

Biocompounds released into the rhizosphere can influence the composition and abundance of soil microbial communities by providing nutrients, acting as signaling molecules, or selectively stimulating or inhibiting particular microorganisms. Root-derived sugars, amino acids, and organic acids can serve as readily available carbon and energy sources, whereas phenolics, flavonoids, terpenoids, and other secondary metabolites may exert more selective effects on microbial populations. Such compounds can therefore contribute to the formation of microbial niches around plant roots and influence the relative abundance of beneficial, neutral, and potentially harmful microorganisms.

The effects of biocompounds on microbial communities are strongly dependent on their chemical characteristics, concentration, persistence, and environmental context. A compound that stimulates one

microbial group may inhibit another, while mixtures of compounds can produce additive, synergistic, or antagonistic effects. Consequently, the composition of root-derived and microbial-derived biocompounds may contribute to microbial community assembly and functional differentiation within the rhizosphere [26].

4.2 | Effects on Microbial Metabolism and Enzyme Activities

Biocompounds can influence microbial metabolism by serving as growth substrates or by modifying metabolic pathways and extracellular enzyme activities. Easily degradable compounds such as simple sugars, amino acids, and low-molecular-weight organic acids can support microbial respiration and biomass production. In contrast, more structurally complex compounds, including phenolics, lignin-derived molecules, and certain terpenoids, may require specialized enzymatic systems for their transformation.

Microbial enzymes are particularly important in determining the fate of biocompounds in soil. Oxidoreductases, hydrolases, and other extracellular enzymes contribute to the decomposition and transformation of organic molecules and thereby influence carbon turnover and nutrient release. At the same time, biocompounds may alter enzyme activity directly through chemical interactions or indirectly by changing microbial community composition. These reciprocal relationships create feedback mechanisms in which microbial activity determines the persistence of biocompounds, while biocompounds regulate the metabolic potential of microbial communities.

4.3 | Biocompounds in Soil Nutrient Cycling

The influence of biocompounds on nutrient cycling represents one of their major ecological functions in soil systems. Organic acids released by roots and microorganisms can modify local pH and interact with mineral surfaces, facilitating the mobilization of phosphorus and micronutrients. Siderophores produced by microorganisms can chelate iron and alter its availability, thereby affecting microbial competition and plant nutrient acquisition. Similarly, amino acids and other nitrogen-containing compounds can participate in microbial nitrogen metabolism and contribute to the redistribution of nitrogen within the rhizosphere.

Biocompounds can also influence nutrient cycling indirectly by regulating microbial populations involved in decomposition, mineralization, nitrification, denitrification, and other biogeochemical processes. Changes in the quantity and composition of carbon substrates available to microorganisms can modify microbial carbon use and alter the balance between microbial growth, respiration, and organic matter decomposition. Therefore, biocompounds can function as molecular links between plant carbon allocation and soil nutrient dynamics [37–39].

4.4 | Microbial Communication and Community Interactions

Chemical communication is an important component of microbial organization in soil. Microorganisms produce and respond to a diverse range of signaling compounds, including peptides, volatile organic compounds, quorum-sensing molecules, siderophores, and other secondary metabolites. These molecules can influence microbial aggregation, biofilm formation, competition, cooperation, and spatial organization.

Plant-derived compounds can further modify these microbial communication networks. Root exudates may stimulate specific microorganisms or alter signaling pathways within microbial communities, thereby affecting colonization and interactions among microbial populations. Such chemical communication can contribute to the establishment of beneficial microbial associations and influence the capacity of microbial communities to respond to environmental changes [31].

4.5 | Influence on Beneficial and Potentially Harmful Microorganisms

Biocompounds can affect microorganisms with different ecological functions in contrasting ways. Certain compounds promote beneficial microorganisms associated with nutrient mobilization, plant growth promotion, organic matter decomposition, or biological suppression of soil-borne pathogens. Other

compounds may inhibit competing microorganisms or modify the abundance of organisms associated with plant disease.

The outcome of these interactions depends on compound concentration, microbial susceptibility, environmental conditions, and the composition of the surrounding microbial community. Importantly, biocompounds should therefore not be considered universally beneficial or inhibitory. Their ecological effects emerge from interactions among chemical properties, microbial traits, and soil environmental conditions. Understanding these context-dependent effects is essential for evaluating biocompounds' role in sustainable soil management [36].

4.6 | Microbial Transformation and Biodegradation of Biocompounds

Soil microorganisms are major agents responsible for the transformation and degradation of biocompounds. Microbial metabolism can convert complex molecules into smaller compounds that may subsequently enter microbial metabolic pathways, become incorporated into soil organic matter, or undergo further degradation. These transformations influence both the persistence and biological activity of biocompounds in soil.

Microbial transformation can also generate products with properties that differ from those of the original compounds. Consequently, evaluating the environmental role of a biocompound requires consideration not only of its initial concentration but also of its transformation products and their persistence. The rate and pathway of microbial degradation are influenced by temperature, moisture, pH, oxygen availability, soil organic matter, microbial community composition, and the chemical structure of the compound [40].

4.7 | Implications for Soil Functional Stability

Through their effects on microbial diversity, metabolism, communication, and nutrient transformation, biocompounds can contribute to the functional organization of soil microbial communities. Diverse chemical inputs may provide multiple substrates and signaling molecules that support functional complementarity among microorganisms. At the same time, selective stimulation or inhibition of particular microbial groups can modify community structure and influence the resilience of soil processes under environmental stress [35].

The relationship between biocompounds and microbial stability is therefore multidimensional. Rather than acting through a single pathway, biocompounds participate in interconnected networks involving microbial community assembly, metabolic activity, nutrient cycling, and plant–microbe interactions. A systems-level understanding of these processes is particularly important for translating knowledge of biocompound–microbe interactions into sustainable agricultural practices. The major effects of biocompounds on soil microbial processes, together with their potential implications for microbial community structure, nutrient cycling, and overall soil health, are summarized in *Table 3* and schematically illustrated in *Fig. 2*.

Table 3. Major effects of biocompounds on soil microbial processes and their implications for soil health.

Microbial Process	Representative Biocompounds	Major Mechanism/Effect	Potential Implication for Soil Health
Microbial community assembly	Phenolics, flavonoids, organic acids	Selective stimulation or inhibition of microbial groups	Changes in microbial diversity and community structure
Microbial growth and metabolism	Sugars, amino acids, organic acids	Provision of carbon, nitrogen, and energy substrates	Increased microbial biomass and metabolic activity
Extracellular enzyme activity	Phenolics, carbohydrates, proteins	Regulation of enzymatic degradation and substrate transformation	Modification of organic matter decomposition
Nutrient mobilization	Organic acids, siderophores	Mineral dissolution and metal chelation	Increased availability of nutrients such as P and Fe
Nitrogen transformation	Amino acids, peptides, organic carbon compounds	Regulation of microbial nitrogen metabolism	Changes in nitrogen mineralization and transformation

Microbial communication	Peptides, volatile compounds, signaling metabolites	Cell-cell signaling and behavioral regulation	Altered microbial cooperation, competition, and colonization
Pathogen suppression	Phenolics, flavonoids, microbial secondary metabolites	Antimicrobial activity and competitive interactions	Potential reduction of soil-borne pathogen pressure
Biocompound degradation	Organic acids, phenolics, carbohydrates, terpenoids	Microbial enzymatic transformation and mineralization	Regulation of compound persistence and carbon turnover
Soil functional stability	Diverse plant- and microbe-derived compounds	Integrated effects on microbial diversity and functions	Greater functional resilience under environmental variation

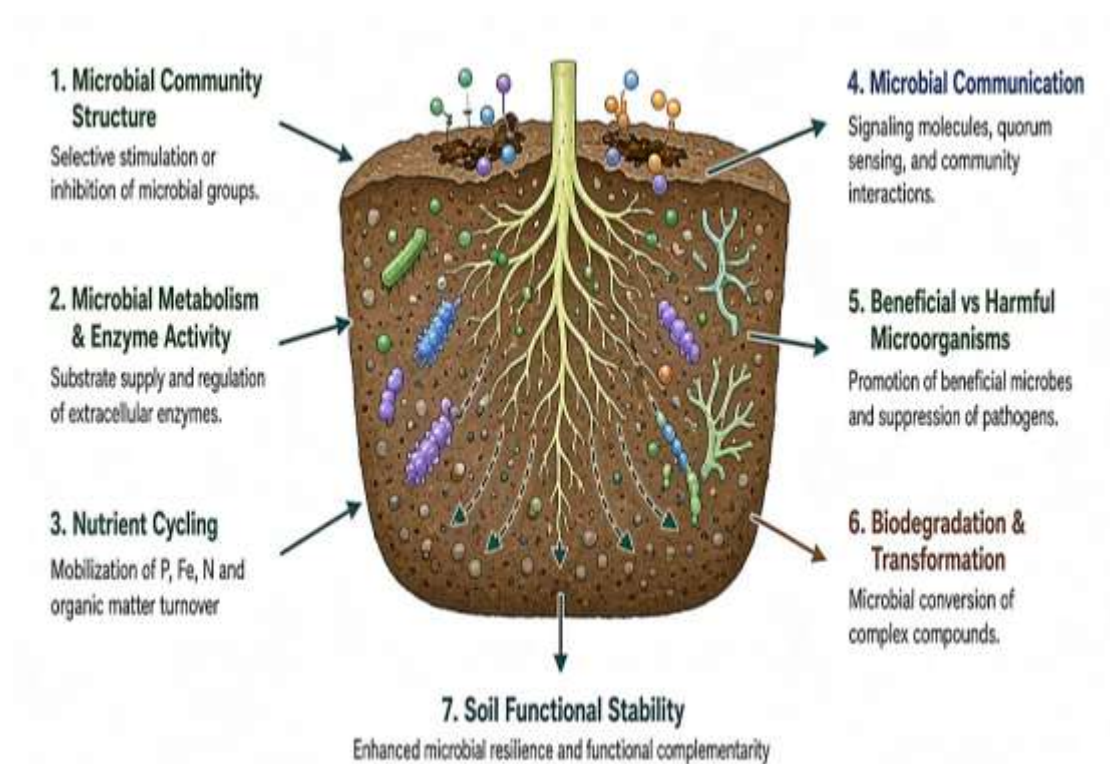


Fig. 2. Major effects of biocompounds on soil microbial processes in the rhizosphere.

5 | Effects on Soil Health and Nutrient Cycling

Soil health is a multidimensional concept encompassing the soil's capacity to sustain plant productivity, support biological activity, regulate nutrient and carbon cycling, and maintain ecological functions under changing environmental conditions. Because biocompounds interact simultaneously with soil microorganisms, minerals, organic matter, and plant roots, they can influence several components of soil

health. Their effects may occur directly through chemical interactions and indirectly through changes in microbial activity, organic matter transformation, and nutrient availability. Understanding these interconnected effects is therefore essential for evaluating the contribution of biocompounds to sustainable soil management [41].

5.1 | Biocompounds and Soil Organic Matter Dynamics

Biocompounds are closely associated with the formation, transformation, and stabilization of soil organic matter. Plant-derived compounds entering soil through root exudation and residue decomposition provide substrates for microbial metabolism and can subsequently contribute to microbial biomass and soil organic matter pools. Phenolic compounds, polysaccharides, proteins, and other complex molecules may also interact with mineral surfaces or existing organic matter, affecting their persistence and stabilization within the soil matrix.

Microbial transformation of biocompounds can further influence the balance between carbon mineralization and carbon stabilization. Easily degradable compounds may rapidly stimulate microbial respiration and carbon turnover, whereas compounds that are strongly associated with minerals or transformed into more persistent organic structures may contribute to longer-term carbon retention. Thus, the quantity, chemical composition, and environmental fate of biocompounds can influence the balance between carbon release and soil carbon storage [40].

5.2 | Regulation of Carbon Cycling

Biocompounds represent important sources of biologically available carbon in soil, particularly within the rhizosphere. Root-derived sugars, amino acids, and organic acids can provide microorganisms with readily accessible carbon substrates, stimulating microbial growth and respiration. This process can accelerate carbon transformation and alter the distribution of carbon between microbial biomass, dissolved organic matter, gaseous products, and more stable soil organic fractions.

The effects of biocompounds on carbon cycling are not necessarily uniform. Rapidly metabolized compounds may promote short-term carbon turnover, whereas microbial processing of plant-derived compounds can contribute to the formation of microbial residues and stable organic matter. Consequently, biocompounds may participate in both carbon mobilization and carbon stabilization, depending on their chemical characteristics and interactions with the soil matrix [42].

5.3 | Influence on Nitrogen Cycling

Nitrogen availability in soil is strongly influenced by microbial activity and the decomposition of organic substrates. Biocompounds containing nitrogen, including amino acids, peptides, and other nitrogenous metabolites, can serve as substrates for microbial growth and contribute to nitrogen transformation. At the same time, carbon-rich biocompounds can modify microbial carbon availability and thereby influence microbial nitrogen demand and competition for inorganic nitrogen.

Biocompounds may consequently affect processes such as nitrogen mineralization, immobilization, nitrification, and denitrification through their effects on microbial communities and substrate availability. The magnitude and direction of these effects depend on the carbon-to-nitrogen characteristics of the compounds, soil environmental conditions, and the functional composition of the microbial community [10–15].

5.4 | Phosphorus Mobilization and Availability

Phosphorus availability is often constrained by interactions with soil minerals, particularly iron- and aluminum-containing minerals in acidic soils and calcium-associated phases in alkaline soils. Organic acids produced by plant roots and microorganisms can modify the chemical environment surrounding phosphorus-containing minerals and facilitate phosphorus mobilization. Siderophores and other metal-chelating

compounds may also influence phosphorus availability indirectly by interacting with metal ions involved in phosphorus retention.

The resulting changes in phosphorus availability can affect both plant nutrient acquisition and microbial activity. However, increased mobilization does not necessarily translate directly into increased plant uptake, because phosphorus may subsequently be re-adsorbed, transformed, immobilized by microorganisms, or transported away from the rhizosphere. Therefore, the ecological significance of biocompound-mediated phosphorus mobilization depends on the balance between mobilization, transformation, and uptake [17].

5.5 | Effects on Micronutrient Availability

Biocompounds can also regulate the mobility and availability of micronutrients through complexation and redox interactions. Organic acids, phenolic compounds, and siderophores can interact with metals such as iron, zinc, manganese, and copper, altering their solubility and accessibility to microorganisms and plants. These interactions are particularly important in the rhizosphere, where root-derived compounds can create localized chemical conditions that differ substantially from those of the surrounding bulk soil.

Such mechanisms can improve the acquisition of essential micronutrients under nutrient-limited conditions. At the same time, strong complexation or increased metal mobility may modify the environmental behavior of potentially toxic elements. Therefore, the effects of biocompounds on metal availability should be considered in relation to both nutrient acquisition and ecological risk [19].

5.6 | Soil Structure, Aggregation, and Water Regulation

Although biocompounds are often discussed primarily in relation to chemical and biological processes, they can also contribute to the physical properties of soil. Polysaccharides and extracellular polymeric substances produced by microorganisms can promote the binding of soil particles and contribute to aggregate formation. Root-derived mucilage and other polymeric compounds may further influence soil pore structure, water retention, and the physical environment surrounding roots.

Changes in soil aggregation can have broader consequences for microbial habitat, aeration, water movement, and organic matter stabilization. Consequently, biocompounds may contribute indirectly to soil structural stability through interactions among roots, microorganisms, organic matter, and mineral particles [21].

5.7 | Biocompounds as Indicators and Drivers of Soil Health

The presence and dynamics of specific biocompounds may provide information about biological activity and functional changes within soil systems. Variations in root exudates, microbial metabolites, phenolic compounds, organic acids, and other molecular markers can reflect changes in plant physiological status, microbial activity, nutrient availability, or environmental stress. Metabolomic and other molecular approaches have therefore created new opportunities for investigating biocompound profiles as potential indicators of soil biological functioning.

At the same time, biocompounds are not merely passive indicators. They can actively modify the biological and chemical environment of soil through their effects on microorganisms, nutrient availability, and soil organic matter dynamics. This dual role as both indicators and functional drivers makes biocompounds particularly relevant to emerging approaches for assessing and managing soil health. The influence of biocompounds on soil health arises from interconnected effects on carbon and nutrient cycling, microbial activity, soil structure, and plant nutrient acquisition [41]. The major relationships between biocompounds, soil processes, and soil health outcomes are summarized in *Table 4*. The interconnected contributions of biocompounds to major components of soil health, nutrient cycling, and soil functional resilience are schematically illustrated in *Fig. 3*.

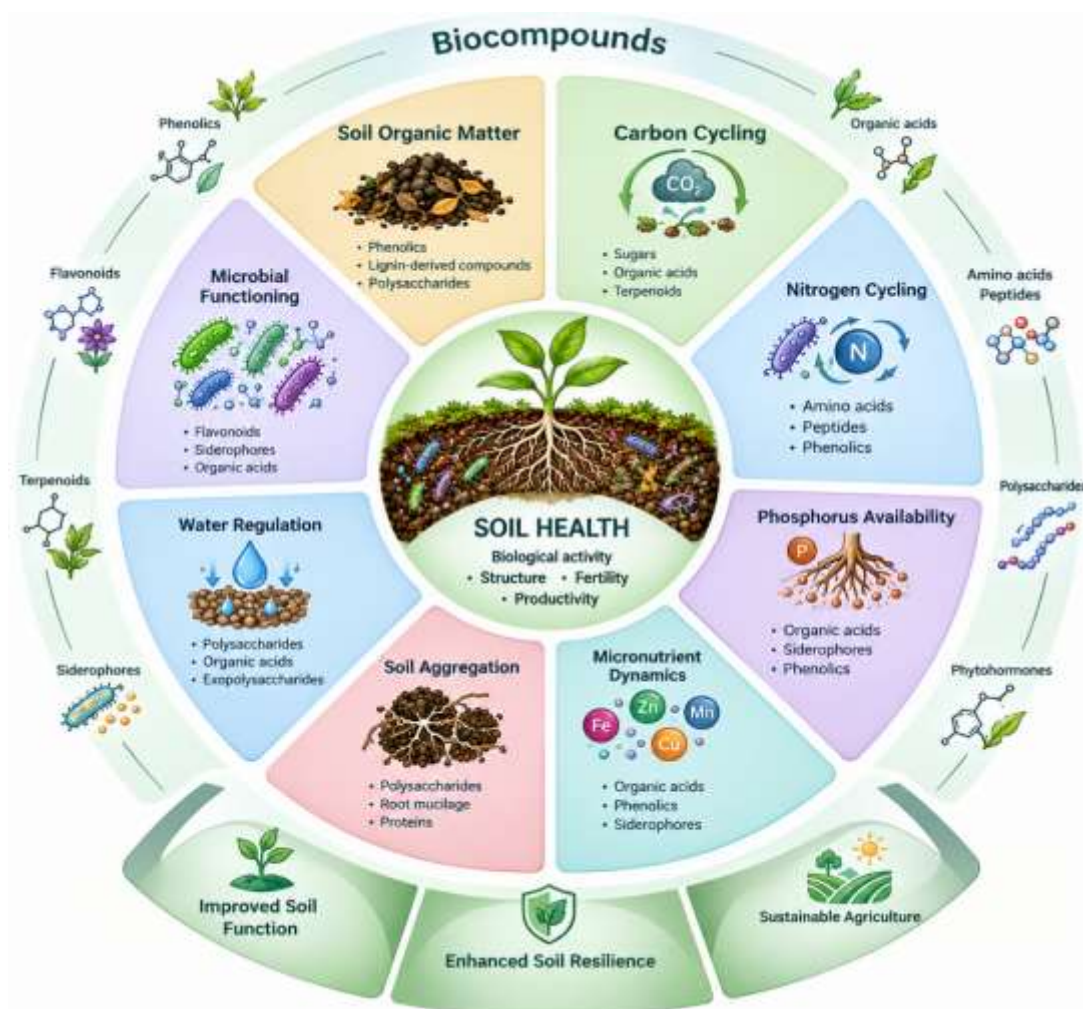


Fig. 3. Conceptual overview of the contributions of biocompounds to soil health, nutrient cycling, and soil functional resilience.

Table 4. Biocompounds, soil processes, and potential implications for soil health.

Soil Health Component	Representative Biocompounds	Main Processes Affected	Potential Implications
Soil organic matter	Phenolics, polysaccharides, proteins, microbial metabolites	Decomposition, stabilization, microbial transformation	Regulation of organic matter persistence and turnover
Carbon cycling	Sugars, organic acids, amino acids	Microbial respiration, biomass production, carbon transformation	Changes in carbon turnover and storage
Nitrogen cycling	Amino acids, peptides, nitrogenous metabolites	Mineralization, immobilization, nitrification, denitrification	Regulation of nitrogen availability
Phosphorus availability	Organic acids, siderophores, phenolics	Mineral dissolution, complexation, phosphorus mobilization	Enhanced or altered phosphorus availability
Micronutrient dynamics	Organic acids, siderophores, phenolics	Metal complexation, solubilization, redox interactions	Modified Fe, Zn, Mn, and Cu availability
Soil aggregation	Polysaccharides, microbial extracellular polymers, root mucilage	Particle binding and aggregate formation	Improved structural stability and pore organization
Water regulation	Root mucilage, extracellular polysaccharides	Water retention and movement through soil pores	Improved rhizosphere water availability
Microbial functioning	Sugars, amino acids, phenolics, microbial metabolites	Microbial growth, signaling, and enzyme activity	Changes in microbial activity and functional stability
Soil health indicators	Root exudates, phenolics, organic acids, microbial metabolites	Metabolic and biochemical responses to environmental conditions	Potential molecular indicators of soil functional status

6 | Biocompounds in Crop Stress Tolerance and Sustainable Agriculture

Agricultural soils are increasingly exposed to environmental stresses associated with climate variability, water limitation, salinity, temperature fluctuations, nutrient imbalance, and soil degradation. These stresses can alter plant physiological processes, disrupt root-microbe interactions, and modify the structure and functioning of soil microbial communities. Biocompounds present in the rhizosphere can contribute to plant and microbial adaptation to such conditions by regulating molecular signaling, nutrient availability, antioxidant responses, and interactions among plants, microorganisms, and the soil matrix [42].

6.1 | Biocompounds and Drought Stress

Water limitation can substantially modify root exudation, microbial activity, and the physicochemical conditions of the rhizosphere. Under drought conditions, changes in the quantity and composition of root-derived sugars, organic acids, amino acids, phenolics, and other metabolites can modify the availability of substrates for microorganisms and alter microbial community structure.

Some biocompounds can contribute to drought adaptation by supporting root development, maintaining rhizosphere microbial activity, or influencing the retention and distribution of water around roots. Microbial extracellular polysaccharides may improve soil aggregation and contribute to the formation of microsites with greater water-holding capacity. At the plant level, changes in signaling and antioxidant-related metabolites can also contribute to the maintenance of cellular homeostasis under water limitation.

The interaction between drought-induced changes in plant metabolism and soil microbial processes is particularly important. Drought can alter microbial diversity and activity, while microorganisms capable of utilizing or transforming plant-derived compounds may modify the chemical environment surrounding roots. Thus, biocompounds can participate in feedback mechanisms that influence plant-microbe interactions during water stress [39].

6.2 | Biocompounds and Salinity Stress

Soil salinity affects plants through osmotic stress, ionic imbalance, and secondary oxidative damage. Salinity can also modify microbial community composition and reduce the availability of water and nutrients in the rhizosphere. In response to saline conditions, plants may alter the production and release of organic acids, amino acids, phenolic compounds, and other metabolites.

These compounds can influence rhizosphere chemistry and microbial activity and may contribute to the mobilization of nutrients under conditions in which nutrient uptake is restricted. Interactions between root-derived compounds and microorganisms can further affect microbial colonization and functional activity around roots. In parallel, microbial metabolites may influence plant physiological responses and contribute to improved tolerance to osmotic and ionic stress.

The effects of biocompounds under saline conditions are highly context-dependent. Their contribution to stress tolerance depends on plant species, microbial community composition, soil properties, salinity level, and the chemical characteristics of the compounds involved. Therefore, the same biocompound may produce different outcomes under different soil and environmental conditions [30–34].

6.3 | Biocompounds and Temperature Stress

Temperature fluctuations can influence both plant metabolism and microbial processes in soil. High temperatures may accelerate the degradation of labile organic compounds while simultaneously increasing water loss and oxidative stress. Low temperatures, in contrast, can reduce microbial metabolic activity and slow nutrient transformation.

Biocompounds may contribute to adaptation to temperature stress by acting as substrates, signaling molecules, or components of plant and microbial stress-response pathways. Changes in root exudation can modify the availability of carbon substrates for microorganisms, while microbial metabolites may influence plant responses to thermal stress. The persistence and transformation of biocompounds are also temperature-dependent, linking environmental conditions with their biological activity and fate in soil [35].

6.4 | Biocompounds and Oxidative Stress

Environmental stresses frequently increase the production of reactive oxygen species in plant tissues and can disturb cellular redox balance. Phenolic compounds, flavonoids, and other antioxidant-associated metabolites can participate in mechanisms that limit oxidative damage. In addition, interactions between plants and rhizosphere microorganisms may modify the production or transformation of metabolites involved in redox regulation.

Microorganisms can also produce metabolites and enzymes that influence oxidative processes in the rhizosphere. These interactions may contribute to maintaining a more favorable biochemical environment around roots during stress. However, the antioxidant effects of individual compounds depend on their concentration, chemical structure, stability, and interactions with other compounds and soil components [32].

6.5 | Biocompounds and Nutrient Stress

Nutrient deficiency can substantially modify plant metabolism and root exudation. Under nutrient-limited conditions, plants may increase the release of organic acids, amino acids, phenolics, and other compounds that influence nutrient mobilization and microbial interactions. These changes can modify the chemical environment of the rhizosphere and promote interactions with microorganisms capable of transforming or mobilizing nutrients.

For example, organic acids can contribute to the mobilization of phosphorus and micronutrients, while siderophore production by microorganisms can facilitate iron acquisition. Such processes illustrate how plant-derived and microbial-derived biocompounds can function as components of nutrient acquisition strategies. Their effectiveness, however, depends on the chemical characteristics of the soil and the availability of complementary microbial functions [36–38].

6.6 | Biocompounds and Soil-Plant-Microbe Resilience

The capacity of agricultural systems to maintain productivity under environmental stress depends partly on the stability and adaptability of soil-plant-microbe interactions. Biocompounds contribute to these interactions by mediating chemical communication, providing metabolic substrates, modifying nutrient availability, and influencing microbial community composition.

A resilient rhizosphere can be viewed as a dynamic system in which plants modify their chemical environment in response to stress, microorganisms respond to these changes, and microbial transformations subsequently influence plant performance. This reciprocal feedback can contribute to the maintenance of nutrient acquisition and biological activity under unfavorable conditions.

Importantly, resilience is not determined by the abundance of a single biocompound. Rather, it emerges from complex interactions among compound mixtures, microbial communities, plant genotypes, and environmental conditions. This perspective emphasizes the importance of studying biocompound networks rather than isolated molecules when evaluating stress tolerance in agricultural soils [30].

6.7 | Contribution to Sustainable Agriculture

The potential role of biocompounds in sustainable agriculture arises primarily from their capacity to influence naturally occurring soil and plant processes. By supporting beneficial microbial interactions, nutrient mobilization, soil organic matter dynamics, and plant adaptation to environmental stress, biocompounds may contribute to agricultural systems that rely more strongly on biological processes.

This approach is consistent with broader efforts to improve resource-use efficiency, maintain soil health, and reduce unnecessary chemical inputs. However, the practical use of biocompounds requires careful consideration of their environmental persistence, dose-dependent effects, interactions with native microbial communities, and performance under field conditions. Laboratory observations cannot always be directly translated to agricultural systems because field soils contain complex and heterogeneous biological and physicochemical environments [22–26]. The integrated relationships among environmental stresses, biocompound-mediated mechanisms, and potential agricultural outcomes are schematically illustrated in Fig. 4. The major relationships between environmental stresses, biocompound-mediated processes, and potential agricultural outcomes are summarized in Table 5.

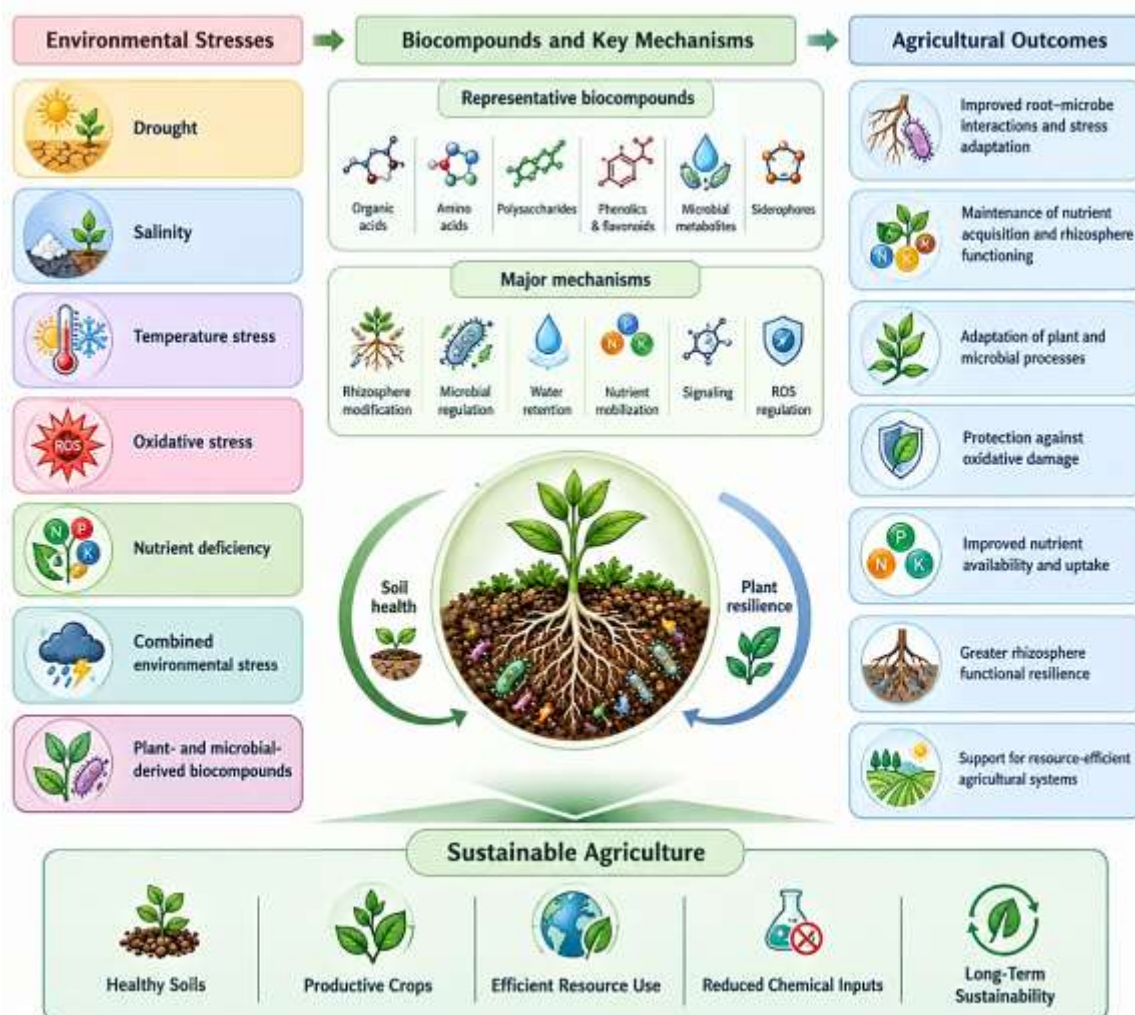


Fig. 4. Conceptual framework illustrating the relationships among environmental stresses, biocompound-mediated mechanisms, and sustainable agricultural outcomes.

Table 5. Biocompounds associated with environmental stress responses and their potential implications for sustainable agriculture.

Environmental Stress	Representative Biocompounds	Major Mechanisms	Potential Implications
Drought	Organic acids, amino acids, polysaccharides, phenolics	Rhizosphere modification, microbial regulation, water retention, signaling	Improved root-microbe interactions and stress adaptation
Salinity	Organic acids, amino acids, phenolics, microbial metabolites	Nutrient mobilization, osmotic adaptation, microbial interactions	Maintenance of nutrient acquisition and rhizosphere functioning

Table 5. Continued.

Environmental Stress	Representative Biocompounds	Major Mechanisms	Potential Implications
Temperature stress	Sugars, organic acids, phenolics, microbial metabolites	Substrate availability, metabolic regulation, stress signaling	Adaptation of plant and microbial processes
Oxidative stress	Phenolics, flavonoids, antioxidant-associated metabolites	Reactive oxygen species regulation and redox interactions	Protection against oxidative damage
Nutrient deficiency	Organic acids, amino acids, siderophores, phenolics	Nutrient mobilization and microbial-mediated acquisition	Improved nutrient availability and uptake
Combined environmental stress	Multiple biocompound classes	Integrated plant–microbe–soil responses	Greater rhizosphere functional resilience
Sustainable soil management	Plant- and microbial-derived biocompounds	Microbial regulation, nutrient cycling, soil health maintenance	Support for resource-efficient agricultural systems

7 | Environmental Implications and Ecological Considerations

The environmental behavior of biocompounds is determined by a complex combination of their chemical characteristics, biological origin, soil properties, and interactions with microorganisms, minerals, organic matter, and plant roots. Once released into soil, biocompounds may undergo adsorption, desorption, dissolution, complexation, oxidation, reduction, microbial degradation, or incorporation into soil organic matter. These processes determine their persistence, mobility, bioavailability, and biological activity and ultimately influence their ecological significance. Therefore, evaluating biocompounds in agricultural systems requires consideration not only of their biological functions but also of their environmental fate and potential effects on surrounding soil communities [40]. The major environmental fate pathways of biocompounds, the factors controlling their behavior, and their potential ecological implications in soil systems are schematically illustrated in *Fig. 5*.

The persistence of a biocompound in soil is particularly important because prolonged residence may increase its influence on microbial communities and soil processes, whereas rapid degradation may limit its biological activity. Labile compounds such as simple sugars and low-molecular-weight organic acids are generally subject to rapid microbial transformation, while more complex phenolics, terpenoids, polymeric compounds, and compounds strongly associated with mineral or organic phases may persist for longer periods. However, persistence is not an intrinsic property of a compound alone. Soil pH, temperature, moisture, redox conditions, organic matter content, mineral composition, and microbial activity can substantially modify its transformation rate. Consequently, the same biocompound may exhibit different environmental behavior across soil types and climatic conditions.

Bioavailability represents another important determinant of ecological function. A compound may be present in soil but unavailable for microbial uptake, plant absorption, or biological interaction because of adsorption to mineral surfaces, incorporation into organic matter, or chemical transformation. Conversely, desorption or microbial transformation can increase the fraction available for biological activity. The dynamic equilibrium between dissolved, sorbed, transformed, and biologically available fractions therefore plays a central role in determining the actual effects of biocompounds within soil systems [40–42].

Biocompounds may also influence soil ecological networks beyond their direct target interactions. Changes in the concentration of root-derived metabolites can alter microbial community composition, while microbial transformation of these compounds can generate secondary metabolites with distinct biological properties. Such changes may affect organisms that were not directly associated with the original biocompound, including microorganisms involved in decomposition, nutrient cycling, and plant health. These indirect effects highlight the importance of considering soil as an interconnected ecological network rather than a collection of isolated chemical interactions [30].

The effects of biocompounds on non-target organisms require particular attention when compounds are intentionally introduced into agricultural soils or when their concentrations are substantially modified through changes in plant or microbial activity. Beneficial microorganisms, decomposers, fungi, soil invertebrates, and other components of soil biodiversity may respond differently to the same compound. A biocompound that stimulates one functional group may inhibit another, potentially altering community structure and ecological interactions. Such effects may be transient and reversible or may persist when compounds are resistant to degradation or repeatedly introduced into the soil environment [31].

Interactions between biocompounds and potentially toxic elements also have important environmental implications. Organic acids, phenolics, and siderophores can modify the solubility and mobility of metals through complexation and changes in the local chemical environment. These interactions may increase the availability of essential micronutrients but can also alter the mobility of potentially toxic elements under specific conditions. The environmental outcome therefore depends on the type and concentration of the compound, the chemical form of the metal, soil properties, and the capacity of plants and microorganisms to absorb or transform the resulting complexes.

Climate and environmental change may further modify the fate and function of biocompounds in soil. Changes in temperature, precipitation patterns, soil moisture, atmospheric carbon dioxide, and vegetation composition can alter root exudation, microbial metabolism, decomposition rates, and soil physicochemical conditions. These changes may subsequently affect the production, transformation, and persistence of biocompounds. Under such circumstances, biocompounds may contribute to feedback mechanisms linking plant responses, microbial processes, and soil environmental conditions.

Another important consideration is the distinction between natural occurrence and external application of biocompounds. Naturally produced compounds are continuously introduced into soil through roots, residues, and microbial metabolism, generally as part of dynamic ecological processes. In contrast, deliberate external application can produce concentrations or exposure patterns that differ from natural conditions. Consequently, results obtained from experiments using purified compounds or relatively high concentrations should be interpreted cautiously when extrapolating to natural agricultural systems. Mixtures of compounds, repeated exposure, and interactions with native soil communities should be considered in future environmental assessments [32–38].

Advanced analytical approaches are increasingly capable of addressing these complexities. Metabolomics, high-resolution mass spectrometry, molecular microbiology, metagenomics, transcriptomics, and spatially resolved analytical techniques can help characterize the distribution and transformation of biocompounds within soil and rhizosphere environments. Integrating chemical and biological datasets can reveal relationships between compound profiles, microbial functions, nutrient cycling, and plant responses that cannot be identified through conventional measurements alone. Such approaches may also support the development of molecular indicators for monitoring soil ecological changes [39].

The environmental implications of biocompounds depend on the balance between production, transformation, persistence, bioavailability, and biological activity. Their ecological roles cannot be fully understood by examining individual compounds independently of their environmental context. A comprehensive assessment should consider compound mixtures, soil characteristics, microbial community structure, plant responses, transformation products, and exposure duration. This integrated perspective is particularly important for developing sustainable agricultural strategies that enhance beneficial biological processes while minimizing unintended ecological effects [40].

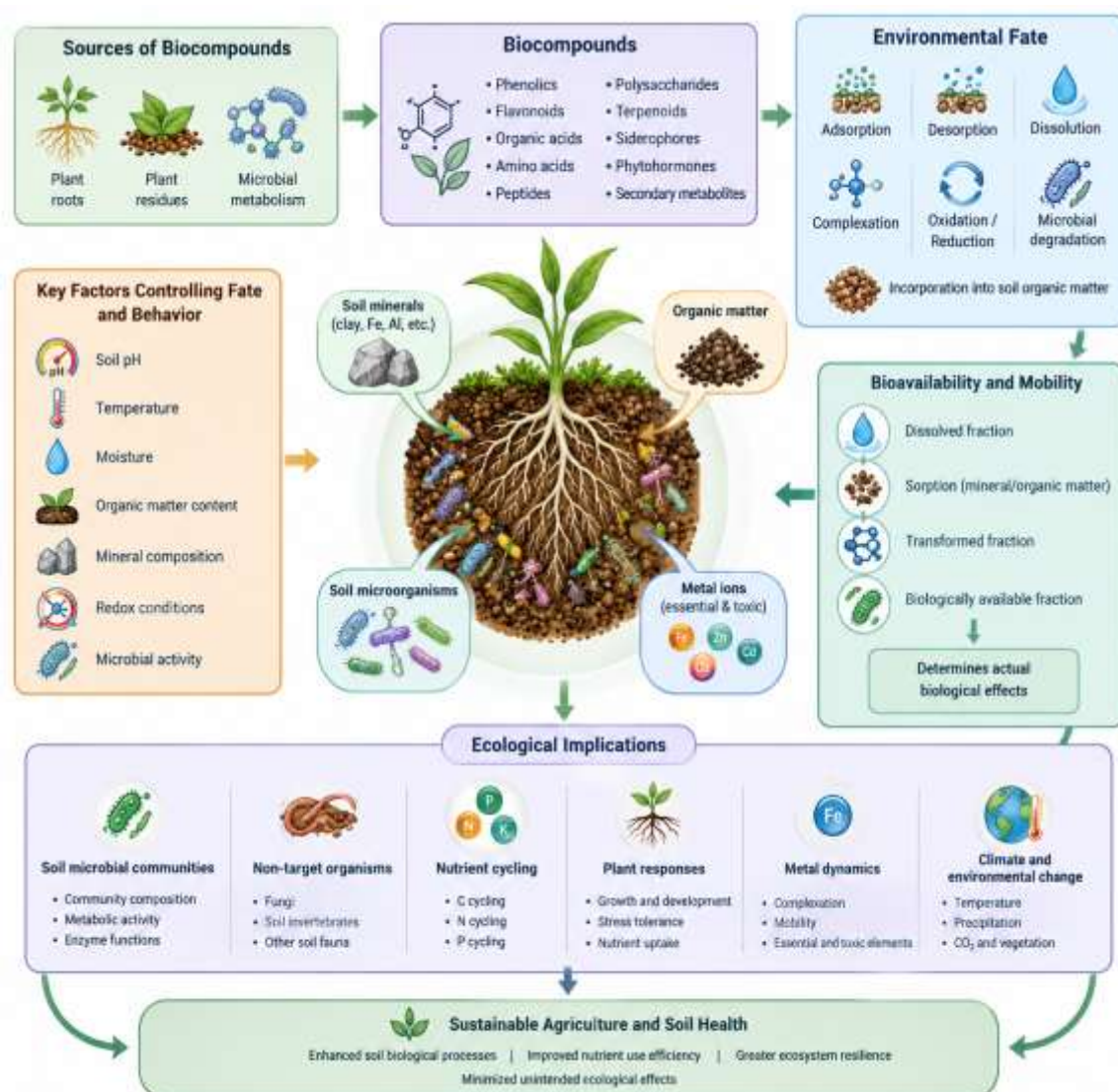


Fig. 5. Environmental fate, bioavailability, and ecological implications of biocompounds in soil systems.

8 | Emerging Technologies and Future Perspectives

Recent advances in analytical, molecular, and computational technologies are providing new opportunities to investigate the complex roles of biocompounds in soil and agricultural ecosystems. Conventional studies have often focused on individual compounds or isolated biological responses, whereas current approaches increasingly consider biocompound networks, microbial communities, and soil-plant interactions as interconnected systems. This transition from single-factor analysis toward integrated, systems-level approaches is particularly important because the environmental behavior and biological effects of biocompounds are strongly influenced by their chemical context and interactions with multiple components of the soil ecosystem [36–39].

Metabolomics represents one of the most promising approaches for characterizing the diversity and dynamics of biocompounds in soil and rhizosphere environments. High-resolution analytical platforms can detect large numbers of metabolites and provide information about changes in chemical profiles associated with plant development, nutrient availability, microbial colonization, and environmental stress. When combined with spatially resolved analytical techniques, metabolomics can also help identify the distribution of specific compounds around roots and within microscale soil environments. Such information can improve

understanding of how localized chemical gradients regulate microbial recruitment and nutrient transformation [32].

Integrating metabolomics with metagenomics, metatranscriptomics, and other omics approaches can provide a more comprehensive understanding of relationships between biocompound production and microbial function. Metagenomic analyses can reveal the functional potential of microbial communities, while transcriptomic approaches can provide information about actively expressed metabolic pathways. Linking these datasets with metabolite profiles may help identify microorganisms responsible for the production or transformation of specific compounds and clarify the molecular mechanisms underlying plant-microbe interactions. Such multi-omics frameworks can move research beyond correlations toward a more mechanistic understanding of soil biological processes [34].

Advances in spatial biology and imaging technologies may further improve the characterization of biocompound dynamics in heterogeneous soil environments. The rhizosphere contains steep chemical and biological gradients that cannot always be adequately represented by bulk soil measurements. Spatially resolved approaches can help determine where compounds are produced, where they accumulate, and how their distributions correspond to microbial colonization and root activity. Combining spatial information with chemical and microbial datasets may therefore provide a more realistic representation of soil-plant-microbe interactions [40].

Microbiome engineering represents another emerging direction for sustainable agriculture. Rather than focusing exclusively on the direct application of individual compounds, future strategies may seek to manipulate microbial communities capable of producing, transforming, or responding to beneficial biocompounds. The establishment of microbial consortia with complementary metabolic functions could potentially enhance nutrient cycling, improve plant stress responses, and increase the functional stability of the rhizosphere. However, successful microbiome engineering requires consideration of native microbial communities, soil characteristics, ecological competition, and the stability of introduced microbial functions under field conditions [41].

Computational approaches and Artificial Intelligence (AI) may also contribute to the interpretation of complex biocompound-microbiome datasets. Large datasets generated by metabolomics, metagenomics, soil monitoring, and environmental measurements can contain nonlinear relationships that are difficult to identify using conventional statistical approaches alone. Machine-learning and data-integration methods may help identify patterns linking specific chemical profiles with microbial functions, nutrient availability, plant performance, or environmental stress responses. Such predictive approaches could eventually support the identification of molecular indicators of soil health and the development of more precise soil management strategies [42].

Precision agriculture provides an additional framework in which knowledge of biocompounds could be translated into spatially and temporally targeted management practices. Soil heterogeneity means that the concentration and activity of biocompounds may differ substantially across fields and even within individual root zones. Integrating molecular information with sensors, remote observations, soil mapping, and site-specific management could enable more targeted interventions based on the biological condition of individual soil zones. Such approaches may improve resource-use efficiency while reducing unnecessary inputs and disturbance of soil ecological processes.

Future research should also place greater emphasis on field-scale validation. Many current studies are conducted under controlled laboratory or greenhouse conditions, where environmental variables can be precisely regulated, but soil complexity is reduced. Field soils contain diverse microbial communities, heterogeneous mineral and organic phases, fluctuating moisture and temperature conditions, and variable plant-microbe interactions. Therefore, compounds or microbial functions that produce consistent effects under controlled conditions may behave differently under agricultural field conditions. Long-term and multi-location studies are needed to determine the reproducibility, persistence, and ecological relevance of biocompound-mediated effects [34–38].

Another important research priority is the development of standardized approaches for measuring biocompound concentrations, transformation products, bioavailability, and biological effects. Differences in extraction procedures, analytical platforms, soil incubation conditions, and reporting methods can make comparisons among studies difficult. Harmonized methodologies and comprehensive metadata would improve the reproducibility of research and facilitate the integration of datasets across different soil types, crops, and environmental conditions.

Future investigations should increasingly consider biocompounds as dynamic components of ecological networks rather than isolated functional molecules. The combined analysis of compound mixtures, microbial communities, plant phenotypes, soil physicochemical properties, and environmental variables could reveal emergent properties that are not predictable from individual components. This systems perspective may provide a stronger scientific foundation for designing agricultural practices that enhance natural soil functions while maintaining ecological stability [39].

Ultimately, the integration of advanced analytical technologies, multi-omics, microbiome engineering, computational modeling, and precision agriculture has the potential to transform the study of biocompounds from descriptive characterization toward predictive and mechanistic environmental science. Future progress will depend on connecting molecular-scale observations with field-scale ecological processes and translating this knowledge into management strategies that are effective, reproducible, and environmentally responsible.

9 | Challenges and Research Gaps

Despite increasing evidence for the ecological importance of biocompounds in soil systems, several challenges limit a comprehensive understanding of their roles in soil health and sustainable agriculture. One major challenge is the chemical and biological complexity of soil environments. Biocompounds rarely occur as isolated molecules; instead, they are present as mixtures that interact with minerals, organic matter, water, plant roots, and diverse microbial communities. These interactions can modify their stability, bioavailability, and biological activity, making it difficult to attribute observed effects to individual compounds or specific molecular mechanisms.

A further challenge is the strong dependence of biocompound activity on environmental conditions. Soil pH, texture, organic matter content, moisture, temperature, redox conditions, and mineral composition can substantially influence the production, transformation, adsorption, and persistence of biocompounds. Differences in plant genotype, developmental stage, root architecture, and microbial community composition can further modify their abundance and function. As a result, findings obtained from one soil-plant system cannot necessarily be generalized to other agricultural environments [38–42].

The distinction between concentration and biological availability also remains an important research gap. Measurements of total compound concentration do not necessarily represent the fraction that is accessible to microorganisms or plants. Adsorption to minerals, incorporation into soil organic matter, complexation with metals, and microbial transformation can substantially alter the biologically available fraction. Future studies should therefore combine chemical quantification with measurements of bioavailability and biological responses to provide a more realistic assessment of biocompound function [29].

Another limitation concerns the frequent use of simplified experimental systems. Laboratory and greenhouse experiments provide valuable information about molecular mechanisms under controlled conditions, but they often involve relatively uniform soils, selected microbial populations, individual compounds, or controlled environmental conditions. Agricultural soils are considerably more heterogeneous and contain complex microbial communities exposed to fluctuating temperature, moisture, nutrient availability, and management practices. Consequently, greater emphasis should be placed on field experiments and long-term studies that evaluate the stability and reproducibility of biocompound-mediated effects under realistic environmental conditions [27].

The role of compound mixtures represents another important area requiring further investigation. In natural rhizosphere environments, plants and microorganisms release numerous compounds simultaneously, and their combined effects may differ substantially from those of individual molecules. Mixtures can produce additive, synergistic, or antagonistic interactions, while transformation of one compound may generate products that influence the activity of other compounds. Understanding these interaction networks will require experimental designs that move beyond single-compound approaches and incorporate realistic chemical combinations [21].

The ecological consequences of modifying biocompound profiles also require greater attention. Increasing the availability of a compound that benefits a particular microbial group may unintentionally alter other microbial populations or affect non-target organisms. Similarly, changes in metal mobility caused by organic acids or chelating compounds may influence both nutrient acquisition and the environmental behavior of potentially toxic elements. Comprehensive assessments should therefore evaluate both intended effects and possible indirect consequences across multiple levels of the soil ecosystem [22].

Standardization remains another significant limitation. Differences in sampling strategies, extraction methods, analytical platforms, experimental duration, compound concentrations, and reporting practices make it difficult to compare results among studies. The development of standardized protocols for soil and rhizosphere sampling, biocompound extraction, metabolite identification, bioavailability assessment, and ecological evaluation would improve reproducibility and facilitate data integration. Open sharing of analytical and environmental metadata would further strengthen comparative and meta-analytical research [38].

The connection between molecular-scale mechanisms and field-scale soil functions is also insufficiently resolved. Omics and advanced analytical approaches can identify large numbers of compounds and molecular responses, but translating these observations into measurable changes in soil fertility, crop performance, nutrient-use efficiency, or environmental sustainability remains challenging. Future research should therefore integrate molecular measurements with functional indicators such as microbial biomass, enzyme activities, nutrient fluxes, soil aggregation, plant productivity, and long-term soil carbon dynamics.

Another research priority is the development of predictive frameworks capable of identifying when and under which environmental conditions particular biocompounds are likely to produce beneficial or adverse effects. Machine-learning approaches, mechanistic modeling, and multi-omics data integration may provide useful tools for addressing this challenge. However, predictive models will require sufficiently large, standardized, and experimentally validated datasets representing diverse soil types, crops, climates, and management systems [40].

Long-term ecological stability should also become a central consideration in future studies. Short-term increases in microbial activity or nutrient availability do not necessarily indicate sustained improvements in soil health. Repeated changes in biocompound concentrations may alter microbial community structure, organic matter dynamics, or nutrient cycling over longer periods. Longitudinal studies are therefore needed to distinguish transient responses from persistent changes in soil ecosystem functioning.

Future research should move toward integrative approaches that combine chemical characterization, molecular biology, microbiome analysis, soil physicochemical measurements, plant physiology, and field-scale ecological assessment. Greater attention to compound mixtures, transformation products, bioavailability, non-target effects, and environmental variability will be essential for developing a mechanistic and ecologically realistic understanding of biocompounds. Addressing these gaps can help establish stronger connections between fundamental knowledge of soil molecular interactions and practical strategies for maintaining soil health and advancing sustainable agriculture [42].

10 | Conclusion

Biocompounds are integral components of soil-plant-microbe systems and contribute to the regulation of molecular interactions, microbial processes, nutrient cycling, and plant responses to environmental stress.

Their effects extend beyond individual biochemical activities and emerge from dynamic interactions with soil minerals, organic matter, microorganisms, and plant roots. Through these interactions, biocompounds can influence carbon and nutrient transformations, microbial community organization, soil structural properties, and the biological processes underlying soil health.

The environmental fate of biocompounds is equally important for understanding their ecological functions. Their persistence, transformation, adsorption, bioavailability, and interactions with metals determine the extent and duration of their biological effects. These properties are strongly influenced by soil characteristics and environmental conditions, emphasizing the need to consider biocompounds within their specific ecological context rather than as isolated molecules. Recent advances in metabolomics, multi-omics, microbiome analysis, spatial technologies, and computational approaches provide new opportunities to investigate these complex interactions at multiple scales [39–41].

Despite substantial progress, important challenges remain regarding the behavior of biocompound mixtures, transformation products, bioavailability, non-target effects, and translation of laboratory findings to field conditions. Future research should integrate molecular characterization with microbial ecology, soil physicochemistry, plant physiology, and long-term field assessment. Such an integrated perspective can strengthen the mechanistic understanding of biocompounds and support the development of sustainable agricultural strategies that enhance soil health, improve resource-use efficiency, and maintain ecological stability.

Authors' Contributions

All aspects of the research and manuscript preparation were carried out by the author. The author has read and approved the final version of the manuscript.

Data Availability

All data supporting the reported findings in this research paper are provided within the manuscript.

Funding

Not applicable.

Conflict of Interest

The author declares that they do not have any conflict of interest.

Consent for Publication

The author confirms consent for the publication of this work

Ethics Approval and Consent to Participate

This article does not contain any studies with human participants performed by the author.

References

- [1] Gallego, I. (2025). Biocompounds of commercial interest from freshwater and marine phytoplankton. In *The role of plankton in freshwater and marine ecology*. IntechOpen. <https://doi.org/10.5772/intechopen.1008500>
- [2] Alviz-Meza, A., Rojas-Flores, S. J., & Gonzalez-Delgado, A. D. (2026). Research trend in the valorization of Persea Americana: A bibliometric analysis of bioactive compounds, extraction technologies, and applications (2005-2024). *Environmental research, engineering and management*, 82(1), 65–87. <https://doi.org/10.5755/j01.ere.m.82.1.42769>

- [3] Gavrilas, S. (2026). Valorization of sustainable antioxidant sources and new perspectives for utilization. *Processes*, 14(3), 578. <https://doi.org/10.3390/pr14030578>
- [4] Quintin, D., Garcia-Gomez, P., Ayuso, M., & Sanmartin, A. M. (2019). Active biocompounds to improve food nutritional value. *Trends in food science & technology*, 84, 19–21. <https://doi.org/10.1016/j.tifs.2018.03.024>
- [5] Sheikh, Z. U. D., Bharti, A., Kotwal, N., Devi, A., Kothari, R., Pathania, D., & Singh, A. (2026). High-valued biomolecules from algal biomass: Research Gaps, innovative roadmaps for safety and quality assurance. In *Algae: A promising source of food, feed and bioproducts* (pp. 621–655). Springer. https://doi.org/10.1007/978-3-032-22521-4_20
- [6] Bayraktar Ekmekcigil, O., Eroglu, S., Bharadwaj, S., Farooqi, A. A., Gozuacik, D., & Kutlu, O. (2026). Targeting the Autophagy-Apoptosis axis in Osteosarcoma: Therapeutic potential of biocompounds: A review. *Chemical biology & drug design*, 107(2), e70257. <https://doi.org/10.1111/cbdd.70257>
- [7] Ceravolo, G., Ferrandis Rosell, A., Blesa, J., Lopez Malo, D., Scarafoni, A., & Esteve, M. J. (2025). Use of biphasic NADES to evaluate the extraction of biocompounds in hydrophilic phase from Okara. *FEBS OPEN BIO*, 15(Suppl. 2), 201–201. <https://hdl.handle.net/2434/1173873>
- [8] Berradre, M. N., Arroqui, C., Fernández-Pan, I., Beriain, M. J., Ibañez, F. C., & Vírveda, P. (2026). Eco-friendly recovery of biocompounds from agro-industrial by-products using non-thermal processing. *Clean technologies*, 8(3), 64. <https://doi.org/10.3390/cleantechnol8030064>
- [9] Styc, Q., Borrelli, P., Evangelista, S. J., Field, D., Francos, N., Heuser, I., ... & McBratney, A. (2026). Soil health within soil security. *European journal of soil science*, 77(3), e70340. <https://doi.org/10.1111/ejss.70340>
- [10] Joshi, N., Jinger, D., Joshi, S., Joshi, E., Sharma, J. K., Paramesha, V., ... & Madhu, M. (2026). Soil health management strategies for climate-resilient agriculture. *Discover soil*, 3(1), 39. <https://doi.org/10.1007/s44378-026-00194-0>
- [11] Singh, M., & Singh, K. (2026). Enhancing crop productivity and soil health through precision fertigation: Advancements, challenges and future prospects. *Applied water science*, 16(4), 130. <https://doi.org/10.1007/s13201-026-02767-4>
- [12] Kumar, S., Dhyani, B. P., Shahi, U. P., Kumar, S., Singh, S. P., Kumar, Y., ... & Pal, R. (2026). Organic waste recycling for soil amendments: Advancing circular bioeconomy and soil health restoration. *AgriSustain: An international journal*, 4(2), 17–25. <https://doi.org/10.5281/zenodo.21767851>
- [13] Hu, Y., Cross, A., Shen, Z., Bouma, J., & Viscarra Rossel, R. A. (2026). On soil health and the pivotal role of sensing. *Soil*, 12(1), 227–252. <https://doi.org/10.5194/soil-12-227-2026>
- [14] Allam, A. N., El Gamal, S., & Naggar, V. (2011). Bioavailability: A pharmaceutical review. *International journal of novel drug delivery technology*, 1(1), 77–93. https://www.researchgate.net/publication/271832890_Bioavailability_A_Pharmaceutical_Review
- [15] Joshi, N., Kaur, R., & Nawaz, T. (2026). The soil-root nexus: How soil health shapes plant nutrient uptake and food nutritional security. *Plant and soil*, 521, 1145–1173. <https://doi.org/10.1007/s11104-026-08489-5>
- [16] Alewell, C., Gupta, S., Poulenard, J., Niquille, N., Kaiser, A., Shokri, N., ... & Borrelli, P. (2026). A first quantitative assessment of soil health at European scale considering soil genesis. *Journal of plant nutrition and soil science*, 189(1), 6–16. <https://doi.org/10.1002/jpln.70034>
- [17] de Waterbeemd, H., Lennernäs, H., & Artursson, P. (2004). Drug bioavailability. *Methods and principles in medicinal chemistry*, 18. <https://pdfs.semanticscholar.org/97bd/ad11368e3b0609a29cefc55c8f4075475ee.pdf>
- [18] Caldara, M., Di Gregorio, L., Sarvi, M., Graziano, S., Bindo, A., Salo, T., ... & Bevivino, A. (2026). Impacts on soil health of soil improvers derived from agri-food processing residues: A systematic review with a focus on European field studies. *Journal of soil science and plant nutrition*, 26(1), 2858–2883. <https://doi.org/10.1007/s42729-026-03037-7>
- [19] Pradhan, N. C., Gavhane, K. P., Bhalekar, D. G., & Kiran, P. R. (2026). Sustainable agriculture fundamentals. In *Health, nutrition and sustainability* (pp. 609–626). Academic Press. <https://doi.org/10.1016/B978-0-443-32920-3.00026-4>
- [20] Joshi-Saha, A., & Misra, G. (2026). Legume crops and their role in achieving sustainable agriculture. In *Legumes: Genetics and genomics* (pp. 1–17). Springer. https://doi.org/10.1007/978-981-97-7538-5_2-1

- [21] Jia, X., Zhang, W., & Zhu, T. (2026). Agricultural new productive forces driving sustainable agricultural development: Evidence from Anhui province, China. *Sustainability*, 18(2), 792. <https://doi.org/10.3390/su18020792>
- [22] Gokul, S., Mohan, V. A., Sabarivasan, R., Adhisankaran, K., Rao, P. T., Harish, M., & De, S. (2026). Sustainable agriculture toward carbon neutrality: A quantitative and qualitative assessment. *Environmental and sustainability indicators*, 30, 101219. <https://doi.org/10.1016/j.indic.2026.101219>
- [23] Purohit, A., Kounain, S., Madala, C., Chavan, S., Guguloth, N., Kethavathu, S., ... & Thakur, N. R. (2026). Sustainable crops for future food security: Challenges, innovations, and solutions. In *Improving crops for future sustainability and climate resilience* (pp. 1-40). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-95-2754-0_1
- [24] Subramanian, I., Verma, S., Kumar, S., Jere, A., & Anamika, K. (2020). Multi-omics data integration, interpretation, and its application. *Bioinformatics and biology insights*, 14. <https://doi.org/10.1177/1177932219899051>
- [25] Toutain, P.-L., & Bousquet-mélou, A. (2004). Bioavailability and its assessment. *Journal of veterinary pharmacology and therapeutics*, 27(6), 455–466. <https://doi.org/10.1111/j.1365-2885.2004.00604.x>
- [26] Danish, K. A., & Lubhan, S. (2016). Various techniques of bioavailability enhancement: A review. *Journal of drug delivery and therapeutics (JDDT)*, 6(3), 34–41. <https://jddtonline.info/index.php/jddt/article/view/1228>
- [27] Hasin, Y., Seldin, M., & Lusi, A. (2017). Multi-omics approaches to disease. *Genome biology*, 18(1), 83. <https://doi.org/10.1186/s13059-017-1215-1>
- [28] Ongachi, W., Belinder, I., Bhat, B., Hussain, S., & Dub, R. (2026). Strengthening agricultural extension services to enhance farmers' capacity and resilience for sustainable development; a systematic review. *BMC agriculture*, 2(1), 17. <https://doi.org/10.1186/s44399-026-00039-9>
- [29] Qiu, W., Tang, X., Shen, Q., & Yuan, J. (2026). Plant-microbiome interactions for rhizosphere health: A three-step framework for crop resilience. *Plant, cell & environment*. <https://doi.org/10.1111/pce.70837>
- [30] Hartmann, A. (2026). The rhizosphere-A one health concept for co-evolution of beneficial microbes and plants towards sustainable agriculture. *Plant and soil*, 523(2), 763–773. <https://doi.org/10.1007/s11104-025-08056-4>
- [31] Salata, A., Borisova, G., & Maleva, M. (2026). Microbial allies in stress resilience: The role of plant growth-promoting bacteria in crop rhizosphere, endosphere, and phyllosphere. *Journal of agricultural sciences*, 32(2), 202–221. <https://doi.org/10.15832/ankutbd.1770195>
- [32] Adebayo, A. A., & Babalola, O. O. (2026). Rhizosphere microbiome as an underexplored resource for agroecosystem sustainability: Insights from the carrot root zone. *Environmental microbiology reports*, 18(2), e70325. <https://doi.org/10.1111/1758-2229.70325>
- [33] Chen, C., Wang, J., Pan, D., Wang, X., Xu, Y., Yan, J., ... & Liu, G. P. (2023). Applications of multi-omics analysis in human diseases. *MedComm*, 4(4), e315. <https://doi.org/10.1002/mco2.315>
- [34] Adhikary, K., Selim, S., Sarkar, R., Ganguly, K., Das, J., Almuhayawi, M. S., ... & Karak, P. (2026). Synthetic microbiomes in bioengineered rhizospheres: New frontiers for climate-resilient agriculture. *Frontiers in microbiology*, 17, 1780132. <https://doi.org/10.3389/fmicb.2026.1780132>
- [35] Etesami, H. (2026). Grand challenges in rhizosphere research for the next decade. *Rhizosphere*, 38, 101337. <https://doi.org/10.1016/j.rhisph.2026.101337>
- [36] Umutohi, S., Zhang, H., Guo, J., Yu, Z., Shao, H., Yi, X., ... & Yu, Y. (2026). Oral anticancer drug delivery: Strategies for improving bioavailability. *Chinese chemical letters*, 112362. <https://doi.org/10.1016/j.ccl.2026.112362>
- [37] Shahrajabian, M. H., & Sun, W. (2023). Survey on multi-omics, and multi-omics data analysis, integration and application. *Current pharmaceutical analysis*, 19(4), 267–281. <https://doi.org/10.2174/1573412919666230406100948>
- [38] Khalid, N. U. A., Rivera-Delgado, E., & von Erlach, T. (2026). Navigating the complexity of oral peptide delivery: Challenges and strategies to enhance oral bioavailability. *Frontiers in drug delivery*, 6, 1809842. <https://doi.org/10.3389/fddev.2026.1809842>

- [39] Hosszú, Z., Pártos, P., Mahdavi, M., Ujhelyi, Z., Fehér, P., Haimhoffer, Á., ... & Pető, Á. (2026). The role and potential of nanotechnology in improving solubility and enhancing bioavailability. *Pharmaceutics*, 18(4), 478. <https://doi.org/10.3390/pharmaceutics18040478>
- [40] Vandereyken, K., Sifrim, A., Thienpont, B., & Voet, T. (2023). Methods and applications for single-cell and spatial multi-omics. *Nature reviews genetics*, 24(8), 494–515. <https://doi.org/10.1038/s41576-023-00580-2>
- [41] Tiwari, P., Pandey, R., & Chadha, S. (2026). Integrative multi-omics approaches for personalized medicine and health. *Current bioinformatics*, 21(2), 109–121. <https://doi.org/10.2174/0115748936360644250127095005>
- [42] Moar, K., Pant, A., & Maurya, P. K. (2026). Artificial intelligence, machine learning, and multi-omics: The future of cancer and precision oncology. *Indian journal of clinical biochemistry*, 1–18. <https://doi.org/10.1007/s12291-026-01425-5>