

Natural Organic Compounds in Organic Farming: Roles, Mechanisms, and Future Prospects – A Narrative Review

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Abstract: Natural organic compounds (NOCs) derived from plant, animal, microbial, and mineral sources are increasingly recognized as key inputs for sustainable and eco-friendly agricultural systems. These bioactive compounds enhance soil fertility, regulate plant growth, and manage pests and diseases while reducing reliance on synthetic agrochemicals. This narrative review critically synthesizes current knowledge on the classification, mechanistic pathways, and agronomic applications of NOCs within organic farming frameworks. Emphasis is placed on plant- and microbe-derived compounds such as allelochemicals, humic substances, and amino acid hydrolysates, which function as biofertilizers, biostimulants, and biopesticides by modulating nutrient cycling, soil microbial dynamics, and plant stress resilience. Mineral-associated organic compounds, including humic and fulvic acids, further contribute to soil structural stability and nutrient retention. Although numerous studies report yield improvement and enhanced agroecosystem sustainability following NOC application, the evidence base remains constrained by heterogeneous methodologies, variable efficacy across environments, and limited long-term field validation. By integrating mechanistic insights with agronomic outcomes and emerging analytical approaches, this review identifies key limitations, regulatory and standardization challenges, and priority research directions. Future progress will depend on harmonized analytical frameworks, field-scale validation, and scalable formulations aligned with circular bioeconomy principles to enable reliable and widespread adoption of NOCs in sustainable crop production.

Keywords: natural organic compounds; biostimulants; biofertilizers; organic farming; sustainable agriculture; soil microbiota.

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1. Introduction

Agricultural intensification has substantially boosted global food production over the last century; however, it has also generated severe environmental, ecological, and health challenges. Continuous reliance on synthetic fertilizers, pesticides, and other agrochemicals has led to soil degradation, biodiversity loss, groundwater contamination, and greenhouse gas emissions, posing long-term risks to food security and ecosystem resilience [1-5]. As reported by Durán-Lara et al. (2020), the overuse of these inputs introduces persistent xenobiotic residues into soil and water systems, threatening both human and animal health [6,7]. In response, global agricultural policies and research agendas increasingly emphasize sustainability and the transition to environmentally compatible farming systems that minimize synthetic inputs.

Organic farming represents one of the most viable strategies to address these concerns. It emphasizes ecological balance, soil fertility management, and the exclusion of synthetic agrochemicals while integrating natural bioproducts and biological processes to maintain productivity [8,9]. Within this framework, NOCs have gained prominence as eco-friendly agents that enhance soil health, stimulate plant growth, and manage pests and diseases. Derived from diverse biological and mineral sources, NOCs comprise multifunctional bioactive compounds that regulate key biochemical and ecological processes in agroecosystems [10,11]. They act as biofertilizers, biostimulants, and biopesticides, improving nutrient-use efficiency, soil structure, and plant resilience to biotic and abiotic stresses [6].

Recent research highlights that integrating NOCs into organic farming improves soil nutrient dynamics and enhances microbial biodiversity [12-15]. For instance, humic and fulvic acids derived from compost and vermicompost increase cation-exchange capacity and water-holding capacity. In contrast, plant-derived volatiles, such as terpenoids and phenolics, exhibit antimicrobial and insecticidal activity [16,17]. Similarly, microbial and animal by-products provide vital macronutrients and bioactive molecules that enrich soil organic matter and stimulate root development [18,19]. Collectively, these findings suggest the potential of NOCs to serve as integral components of climate-smart and resource-efficient organic systems.

Despite their advantages, challenges persist in standardization, regulatory approval, and large-scale commercialization of NOC-based products. Inconsistent raw-material quality, variability in bioactive composition, and lack of comprehensive field-scale validation limit their wider adoption [6]. Addressing these limitations requires scientific validation, standardized production protocols, and multidisciplinary approaches that integrate chemistry, microbiology, and soil ecology. A systematic understanding of NOC classification, mechanisms of action, and practical applications is therefore essential to harness their full potential in sustainable agriculture. Moreover, existing studies often employ heterogeneous experimental designs, short-term assessments, and non-standardized biochemical characterization, which complicates cross-study comparison and evidence synthesis.

Accordingly, this review synthesizes current knowledge on natural organic compounds relevant to organic farming. It examines their classification based on origin, elucidates mechanisms of action in soil and plant systems, evaluates agronomic and ecological benefits, and identifies the existing challenges and research priorities. By consolidating evidence from recent literature, this work aims to contribute to the optimization and broader utilization of NOCs as foundational tools for environmentally sound agricultural development. Unlike previous reviews that focus on individual compound classes or specific applications, this narrative review provides an integrated and critical synthesis across source categories, mechanistic pathways, and agronomic contexts, while explicitly identifying methodological limitations, regulatory constraints, and priority research directions for scalable and field-relevant implementation.

2. Materials and Methods

The present review was conducted through a structured, transparent process aimed at comprehensively identifying, evaluating, and synthesizing peer-reviewed literature on NOCs and their functional roles in organic farming.

2.1. Literature search and selection criteria.

An extensive literature survey was performed across major scientific databases like Scopus, Web of Science, PubMed, and Google Scholar to capture the broadest possible range of relevant studies. The search strategy combined Boolean operators (*AND*, *OR*) and truncations using keywords such as “*natural organic compounds*,” “*organic farming*,” “*biofertilizers*,” “*biostimulants*,” “*biopesticides*,” “*soil fertility*,” and “*sustainable agriculture*.” Searches were limited to English-language publications. To ensure both historical context and contemporary relevance, literature published between 2000 and 2025 was considered. Only peer-reviewed journal articles, scientific reviews, and authoritative book chapters were included. Titles and abstracts were screened for thematic relevance, focusing on studies that investigated naturally derived compounds from plant, animal, microbial, or mineral sources within the framework of organic or low-input agriculture. Works that dealt exclusively with synthetic agrochemicals or lacked biochemical or agronomic context were excluded. The search strategy was iteratively refined to ensure thematic coverage and conceptual relevance rather than exhaustive numerical enumeration, reflecting the narrative and integrative nature of the review.

2.2. Data extraction and classification.

Each eligible publication was reviewed in full text, and data were extracted systematically according to four analytical domains: Source classification – origin of NOCs categorized as plant-, animal-, microbial-, or mineral-derived; Mechanistic function – biochemical and physiological mechanisms through which NOCs influence soil fertility and plant physiology; Agronomic application – practical use of NOCs as biofertilizers, biostimulants, or biopesticides within organic farming systems; Challenges and limitations – issues relating to formulation, standardization, variability, scalability, and regulatory compliance.

Priority was given to studies that provided verifiable experimental data or well-defined conceptual models. Extracted information included study objectives, methodologies, key findings, and conclusions. Priority was given to results supported by quantitative data or reproducible observations to maintain analytical objectivity.

2.3 Analytical and synthesis approach.

The collected data were synthesized through qualitative thematic analysis, a method well-suited to integrating heterogeneous evidence from experimental and review-based studies. This approach was adopted because the reviewed studies varied widely in experimental design, outcome metrics, crop systems, and analytical endpoints, precluding meaningful quantitative aggregation. The synthesis focused on identifying common mechanistic pathways, agronomic patterns, and conceptual linkages among diverse studies. A comparative interpretation was performed to highlight convergence or divergence in reported outcomes, particularly regarding nutrient mobilization, allelopathic interactions, microbial stimulation, and stress tolerance. The literature was further interpreted within the conceptual framework of sustainable agriculture, emphasizing nutrient recycling, ecological efficiency, and reduced reliance on synthetic inputs. Studies employing advanced analytical and molecular tools, such as metabolomics, proteomics, and microbiome profiling, were critically examined for their contributions to understanding NOC-mediated biochemical and ecological mechanisms.

2.4. Limitations and quality considerations.

The heterogeneity of experimental conditions, geographic contexts, and crop systems among available studies represents an inherent limitation of this review. Because of these differences in design and metrics, a quantitative meta-analysis was not feasible. Formal risk-of-bias scoring and PRISMA-style screening metrics were not applied, as they would imply a level of methodological homogeneity and comparability not present in the underlying literature. Nevertheless, a rigorous qualitative evaluation was undertaken to ensure that only methodologically robust, peer-reviewed sources informed the synthesis. Internal validity, reproducibility, and ecological applicability were used as quality indicators. Despite these constraints, the adopted methodology provides a scientifically defensible framework for summarizing the state of knowledge regarding the classification, mechanisms, and agronomic applications of natural organic compounds in sustainable and organic agriculture.

3. Classification and Sources of Natural Organic Compounds

NOCs encompass a chemically and biologically diverse group of molecules that originate from plants, animals, microorganisms, and mineral materials. These compounds play fundamental roles in maintaining soil fertility, regulating plant physiological functions, and mitigating pest and disease incidence within organic farming systems. Their classification is primarily based on origin and functional attributes, which collectively determine their mode of action and agricultural applications.

3.1. Plant-derived compounds.

Plant-derived NOCs represent the largest and most chemically heterogeneous group, consisting primarily of secondary metabolites such as alkaloids, terpenoids, phenolics, flavonoids, tannins, saponins, and essential oils. These compounds are biosynthesized through complex metabolic pathways, including the shikimic acid, mevalonate, and polyketide pathways, conferring plants with adaptive defence mechanisms against biotic and abiotic stresses. In organic farming, these bioactive substances are harnessed for their biostimulant, allelopathic, and biopesticidal properties.

Essential oils and their active constituents, such as eugenol, thymol, citronellal, and limonene, exhibit potent antifungal and insecticidal effects by disrupting membrane integrity, interfering with enzymatic activity, and impairing signalling pathways in pests and pathogens [16,17]. Essential oils from species such as neem, eucalyptus, and clove have been widely investigated for insecticidal and antifungal activity [20-23]. Similarly, allelochemicals such as coumarins, benzoxazinoids, and glucosinolates released from crop residues, including mustard, rye, and sorghum, suppress weed germination and reduce pathogen load in the rhizosphere [24,25]. Polyphenols and flavonoids enhance soil antioxidant capacity and microbial diversity, thereby promoting nutrient availability and soil resilience. Green manures, composted crop residues, and plant hydrolysates not only improve soil organic carbon but also supply essential micronutrients and signalling molecules that stimulate plant growth and rhizosphere activity [26,27]. Collectively, plant-derived NOCs exhibit broad functional versatility; however, their agronomic performance is strongly context-dependent, varying with compound composition, formulation stability, soil conditions, and crop species.

3.2. Animal-derived compounds.

Animal-based organic compounds are valuable nutrient sources that complement plant inputs in organic farming systems. Typical materials include bone meal, blood meal, fish emulsion, feather meal, and amino acid hydrolysates [28,29]. These inputs are rich in nitrogen, phosphorus, calcium, and bioactive peptides that improve plant vigour and soil fertility [19, 30]. Amino acid hydrolysates derived from the enzymatic breakdown of animal proteins function as natural biostimulants, enhancing root development, chlorophyll synthesis, and abiotic stress tolerance [18, 31].

Fish emulsions and bone meal serve as slow-release nutrient sources that sustain crop nutrition while minimizing leaching losses. Additionally, cow dung and urine are traditional and scientifically validated components of organic formulations such as *panchagavya* and *jeevamrut*, which enhance microbial proliferation, nutrient solubilization, and enzyme activity in soil [32]. By enriching the soil with humic precursors and beneficial microbiota, animal-derived products help restore soil structure and sustain long-term fertility. Despite their nutritional and biostimulant value, the effectiveness of animal-derived inputs is influenced by raw material variability, processing methods, and regulatory constraints governing their use in certified organic systems.

3.3. Microbial-derived compounds.

Microorganisms produce a wide array of bioactive substances, including siderophores, antibiotics, phytohormones, organic acids, and lytic enzymes, that are integral to plant–microbe–soil interactions in organic systems. These microbial-derived NOCs are primarily utilized in the form of biofertilizers, biopesticides, and biostimulants. Species of *Rhizobium*, *Azospirillum*, *Bacillus*, *Pseudomonas*, and *Trichoderma* are among the most widely studied for their role in nutrient mobilization and plant protection [6, 33]. Through nitrogen fixation, phosphate solubilization, and phytohormone production, microbial metabolites promote root elongation and nutrient uptake [34]. For instance, siderophores chelate iron, limiting pathogen access to this essential micronutrient, while organic acids enhance the solubility of mineral phosphates. Certain microbial strains also secrete volatile organic compounds (VOCs) that act as signalling molecules, inducing systemic resistance in plants and improving tolerance to environmental stress [35,36]. Compared with plant- and animal-derived compounds, microbial-derived NOCs often exhibit higher functional specificity but also greater sensitivity to environmental conditions, formulation stability, and host–microbe compatibility. These microbial contributions are essential for sustaining soil microbial diversity and ensuring ecological balance in organically managed systems.

3.4. Mineral-based organic compounds.

Mineral-associated organic compounds occupy a distinctive niche in organic agriculture, bridging inorganic soil components with organic matter. Examples include humic substances (humic and fulvic acids), leonardite extracts, zeolites, and rock phosphate amendments. Humic substances are high-molecular-weight, heterogeneous polymers formed during the decomposition of plant and microbial residues. They enhance soil aggregation, water retention, and cation exchange capacity while stimulating root elongation and nutrient absorption [37,38]. Rock phosphate and silicate minerals provide slow-release macronutrients and improve soil buffering capacity. Zeolites and bentonites act as natural ion exchangers,

improving soil aeration and regulating nutrient dynamics. The integration of these mineral-based compounds with organic inputs improves the long-term fertility and structural stability of soils under organic management [39,40]. Although mineral-associated organic compounds are not biologically synthesized, their interaction with organic matter and microbial processes positions them as critical modulators of NOC-mediated soil functionality.

3.5. Integrative perspective.

The synergy among plant-, animal-, microbial-, and mineral-derived compounds underpins nutrient cycling and ecological stability in organic farming. Plant residues contribute carbon substrates for microbial metabolism, animal by-products supply nitrogenous precursors, microbial metabolites enhance nutrient mobilization, and mineral-organic complexes ensure sustained nutrient availability (Figure 1, Table 1). Table 1 summarizes the functional roles of NOCs across source categories, highlighting convergence in agronomic outcomes despite differences in their biochemical origins and mechanistic pathways.

Table 1. Classification, biochemical mechanisms, and agronomic functions of NOCs commonly utilized in organic farming systems.

Source type	Representative compounds	Major biochemical/functional mechanism	Primary agronomic function
Plant-derived	Phenolics, flavonoids, terpenoids, saponins*, allelochemicals	Antioxidant activity, modulation of plant hormonal pathways, allelopathic interactions, membrane perturbation (for selected compounds)	Biostimulation, pest and weed suppression, and enhancement of plant stress resilience
Animal-derived	Amino acid hydrolysates, bone meal, fish emulsion	Gradual nutrient mineralization, peptide-mediated signalling, stimulation of root metabolism	Soil fertility enhancement, root development, improved nutrient-use efficiency
Microbial-derived	Siderophores, antibiotics, phytohormones, polysaccharides	Nutrient solubilization, induced systemic resistance, and modulation of rhizosphere microbial communities	Disease suppression, plant growth promotion, stabilization of soil biological processes
Mineral-based	Humic and fulvic acids, zeolites, rock phosphates	Chelation and complexation of micronutrients, improvement of cation exchange capacity (CEC), buffering of soil pH, and nutrient release	Soil structure stabilization, nutrient retention, and long-term fertility support

*Note: Saponins are amphiphilic molecules that exhibit both hydrophilic and lipophilic behavior; their agronomic effects arise from surfactant-like properties rather than simple polarity-based interactions.

This integrative classification provides a conceptual foundation for subsequent evaluation of mechanisms, applications, and limitations, while emphasizing that effective NOC deployment depends on coordinated management of biological, chemical, and mineral inputs rather than isolated compound use.

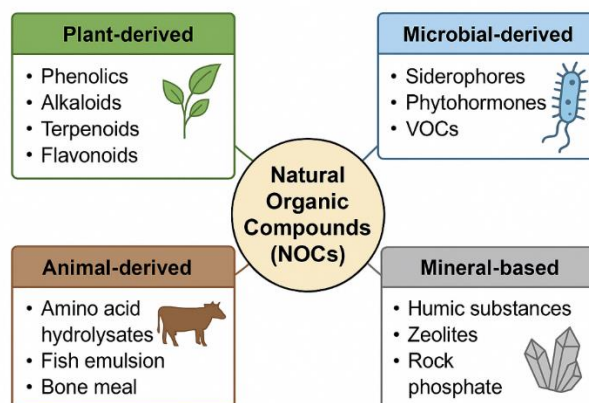


Figure 1. Classification of natural organic compounds.

4. Mechanisms of Action of Natural Organic Compounds

NOCs influence a suite of interconnected biochemical, physiological, and ecological processes that collectively determine soil fertility, plant growth, and crop resilience. Their multifunctional effects arise from dynamic interactions among soil physicochemical properties, microbial communities, and plant metabolic responses. Elucidating these mechanisms is essential for rational optimization of NOC use in organic farming systems. Broadly, NOC action can be grouped into nutrient mobilization and uptake enhancement, regulation of plant growth and physiology, stimulation of soil microbial activity, induction of plant defence responses, and modification of soil physical and chemical properties.

4.1. Nutrient mobilization and uptake enhancement.

A central mechanism underlying NOC functionality is the mobilization, solubilization, and chelation of essential nutrients [41]. Plant- and microbial-derived organic acids (e.g., citric, malic, oxalic, and gluconic acids) locally modify soil chemistry, facilitating the release of phosphorus, iron, and micronutrients from otherwise insoluble complexes [13,33]. Humic and fulvic acids further enhance nutrient availability by forming organo-mineral complexes with Fe, Zn, Cu, and Mn, thereby improving their mobility and root accessibility [35]. These processes collectively increase nutrient diffusion toward plant roots, particularly in low-fertility soils [42]. In biologically active systems, microbial metabolites produced by *Rhizobium*, *Azospirillum*, and *Bacillus* species integrate nitrogen fixation and phosphate solubilization into organic nutrient cycles [36]. Animal-derived amino acid hydrolysates further contribute by modulating membrane transport processes and nutrient uptake efficiency, reinforcing the coupling between soil nutrient pools and plant demand [18,31,43].

4.2. Regulation of plant growth and development.

Many NOCs function as signalling mediators that influence plant hormonal balance and morphogenetic processes. Amino acids, peptides, phenolic compounds, and humic substances interact with phytohormonal pathways involving auxins, cytokinins, gibberellins, and abscisic acid, thereby promoting root elongation, lateral root formation, and chlorophyll biosynthesis [17,44,45]. Indole-containing compounds and tryptophan derivatives, in particular, act as precursors in auxin biosynthesis and play key roles in cell expansion and differentiation. Humic substances also affect photosynthetic performance by enhancing enzymatic activity associated with carbon fixation and energy metabolism. Improved stomatal conductance and CO₂ assimilation efficiency contribute to higher water-use efficiency under organic management [35]. In parallel, volatile organic compounds (VOCs) released by plants and beneficial microorganisms act as airborne signalling molecules, eliciting systemic physiological responses and mediating plant–plant and plant–microbe communication [16].

4.3. Enhancement of soil microbial activity and soil health.

NOCs serve both as substrates and regulators of soil microbial dynamics. Inputs such as compost, green manures, and plant hydrolysates increase the availability of labile carbon and nitrogen, stimulating microbial growth and enzymatic activity [26,27]. Enhanced microbial respiration accelerates organic matter decomposition and nutrient turnover, contributing to improved soil aggregation and organic matter stabilization [10,11]. Microbial-derived

metabolites—including siderophores, antibiotics, and exopolysaccharides—further strengthen beneficial plant–microbe interactions while suppressing pathogenic populations [33,35,36]. Siderophore-mediated iron sequestration enhances plant iron nutrition and restricts pathogen proliferation, whereas extracellular polysaccharides promote biofilm formation and soil moisture retention. Through these direct and indirect pathways, NOCs shape microbial community structure toward a functionally beneficial equilibrium.

4.4. Induction of plant defence mechanisms.

NOCs also act as elicitors of plant defence responses at both local and systemic levels. Phenolics, flavonoids, terpenoids, and selected microbial VOCs activate defence signalling pathways mediated by salicylic acid, jasmonic acid, and ethylene [45-47]. This activation leads to the production of pathogenesis-related proteins, defense enzymes, and phytoalexins, which enhance resistance to bacterial and fungal pathogens [48,49]. Certain plant-derived compounds, including essential oils and alkaloids, exert direct antimicrobial and insecticidal effects by compromising cellular integrity and inhibiting spore germination [17]. Allelopathic metabolites such as benzoxazinoids and glucosinolates further suppress competing weeds and pathogens by interfering with metabolic and structural processes. In addition, humic and fulvic acids reinforce plant antioxidative defence systems, mitigating oxidative stress associated with drought, salinity, and heavy-metal exposure [24,25].

4.5. Improvement of soil physical and chemical properties.

Beyond biochemical and biological interactions, NOCs substantially influence soil physical structure and chemical buffering capacity. Humic substances and composted organic matter promote soil aggregation through stable organo-mineral associations, improving aeration, infiltration, and water-holding capacity [35,38]. These effects are particularly pronounced in degraded or coarse-textured soils. Mineral-associated organic amendments, such as zeolites and bentonites, further contribute by moderating nutrient release, enhancing cation exchange, and reducing leaching losses [39,40]. Together, these modifications create a soil environment that supports sustained nutrient availability and root development.

4.6. Integrated mechanistic perspective.

The mechanisms of NOC action are inherently interconnected rather than isolated.

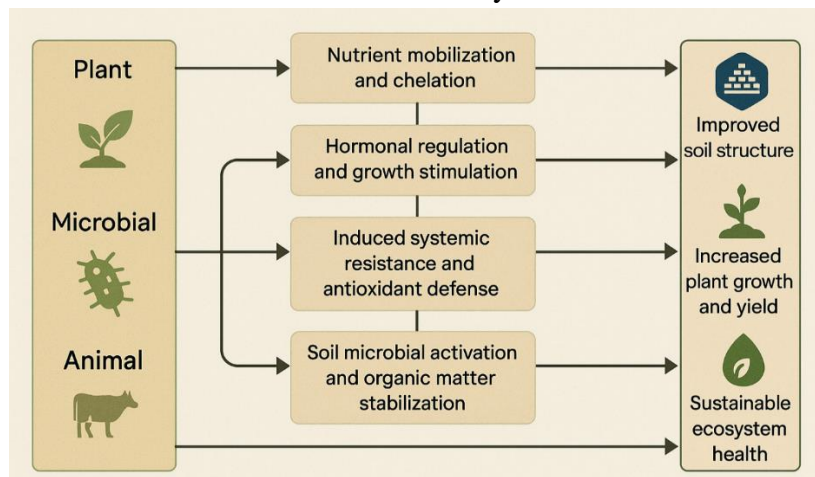


Figure 2. Mechanisms and agronomic functions of NOCs.

Synergistic interactions among organic molecules, microbial communities, and mineral matrices generate self-reinforcing feedback loops that enhance soil functionality and plant performance. Plant residues supply substrates for microbial metabolism, microbial activity generates metabolites that regulate plant physiology and nutrient dynamics, and humic substances mediate exchanges between biotic and abiotic soil components. The cumulative outcome is a more adaptive and resilient agroecosystem capable of maintaining productivity with reduced dependence on external synthetic inputs (Figure 2).

5. Applications of Natural Organic Compounds in Organic Farming

NOCs have emerged as multifunctional inputs in organic farming, offering diverse agronomic, ecological, and economic benefits. Their integration into farming systems not only sustains productivity but also restores soil health, enhances biodiversity, and reduces dependence on synthetic agrochemicals. The practical applications of NOCs can be broadly categorized into soil fertility management, plant growth promotion, pest and disease control, and environmental protection.

5.1. Improvement of soil fertility and nutrient management.

One of the most significant contributions of NOCs is their ability to enhance soil fertility by improving nutrient availability, stabilizing organic matter, and stimulating biological activity. The application of humic substances, compost, biochar, and related organic amendments has been widely associated with increased soil organic carbon content, improved nutrient retention, and greater resilience of soil systems under organic management [35]. These effects translate into improved nutrient-use efficiency and more stable nutrient supply across cropping cycles. Plant- and animal-derived amendments such as green manures, farmyard manure, bone meal, and amino acid hydrolysates act as slow-release nutrient sources that synchronize nutrient supply with crop demand [19, 30]. Green manures, particularly legumes, enrich soils with biologically fixed nitrogen and contribute to the buildup of organic matter. Similarly, composted plant residues promote microbial biomass development and foster self-regulating nutrient cycling processes. Under specific organic management conditions, the application of humic acid-enriched composts has been reported to enhance nutrient uptake efficiency and crop yields by approximately 15–25% [13,26], although outcomes remain dependent on soil type, crop species, and amendment quality. Microbial-derived NOCs further support nutrient management by improving nutrient accessibility and reducing reliance on external inputs. In organically managed systems, microbial inoculants and their metabolites have been associated with improved nutrient acquisition efficiency and more balanced nutrient dynamics, contributing to resilient soil–plant systems [33,36]. The biochemical and microbial mechanisms underlying these effects, including chelation, solubilization, and biological nitrogen inputs, are discussed in detail in Section 4.3.

5.2. Promotion of plant growth and yield.

NOCs are widely applied in organic farming as biostimulants to enhance plant growth and yield performance under diverse agroecological conditions. Field and controlled-environment studies indicate that the use of humic substances and amino acid hydrolysates is associated with improved root development, enhanced photosynthetic capacity, and increased nutrient-use efficiency, collectively contributing to higher biomass accumulation and crop

productivity [18,31]. Plant-derived NOCs, including phenolic compounds and flavonoids, have been shown to support plant growth by improving tolerance to oxidative stress and maintaining physiological balance under organic management. Applications of humic acid at concentrations of 0.2–0.5% have been reported to increase chlorophyll content and net photosynthetic rates by approximately 10–30% in horticultural crops, although responses vary with crop species, developmental stage, and environmental conditions [35]. In addition, microbial-based formulations containing metabolites of genera such as *Trichoderma* and *Azospirillum* are frequently associated with improved root architecture, shoot biomass, and flowering intensity, resulting in measurable yield gains under organic production systems [50]. While positive growth responses are widely reported, the magnitude and consistency of yield enhancement depend on formulation quality, application timing, and site-specific factors. The physiological and biochemical mechanisms underpinning these biostimulatory effects—including hormonal modulation, signaling pathways, and stress-response regulation—are discussed in detail in Section 4.2.

5.3. Biocontrol and pest management.

The biocontrol potential of NOCs represents a central pillar of pest and disease management in organic farming systems. Plant-derived secondary metabolites, including terpenoids, alkaloids, and essential oils, are widely used as botanical pesticides and disease-suppressive agents due to their broad activity spectrum and compatibility with organic certification standards. Essential oils derived from *Ocimum basilicum*, *Azadirachta indica*, and *Cymbopogon citratus* have demonstrated efficacy against economically important insect pests, including *Helicoverpa armigera* and *Spodoptera litura*, as well as several phytopathogenic fungi [51–53]. Allelopathic compounds released from plant residues or applied as bio-based formulations contribute to weed suppression and reduced pest pressure in organically managed fields [24,25]. In parallel, microbial-derived NOCs play a critical role in biological disease control. Formulations containing *Trichoderma* and *Bacillus* species are commonly employed to suppress soil-borne pathogens and enhance crop health, thereby reducing reliance on synthetic pesticides [54]. These biological inputs are increasingly integrated into integrated pest management (IPM) strategies tailored for organic farming. Although the efficacy of NOC-based biocontrol agents is well documented, performance can vary considerably depending on formulation stability, environmental conditions, target organism, and application strategy. The biochemical and microbiological mechanisms underlying pest suppression, including allelopathic interactions, antimicrobial activity, and induced plant defenses, are discussed in detail in Section 4.3.

5.4. Enhancement of plant stress tolerance.

Abiotic stresses, such as drought, salinity, temperature extremes, and nutrient imbalances, pose major constraints on crop productivity in organic farming systems, where synthetic stress-mitigating inputs are restricted. The application of NOCs has consistently been associated with improved plant tolerance to these stresses, thereby contributing to yield stability and resilience under suboptimal environmental conditions. In organic production systems, the use of amino acid hydrolysates, humic substances, and plant-derived bioactive compounds has been linked to improved plant water status, sustained growth, and reduced stress-related yield losses. Field and controlled studies report that crops treated with NOCs

often exhibit enhanced physiological performance and recovery capacity under drought or salinity stress, particularly during early growth and reproductive stages [18,55]. Similarly, microbial-based formulations are frequently associated with improved plant vigor and maintenance of growth under stress-prone conditions [56]. Despite these generally positive outcomes, the effectiveness of NOC-based stress mitigation strategies is influenced by crop species, stress intensity and duration, application timing, and formulation quality. Consequently, stress-alleviating responses are not uniform across environments or production systems. The underlying physiological and biochemical mechanisms responsible for stress tolerance—including osmotic adjustment, antioxidant regulation, and growth modulation—are discussed in detail in Section 4.4.

5.5. Environmental and ecological benefits.

The adoption of NOCs in organic farming contributes significantly to environmental sustainability by reducing agrochemical inputs, enhancing biodiversity, and improving soil and water quality. Replacing or supplementing synthetic fertilizers and pesticides with NOC-based inputs lowers the accumulation of chemical residues in soil and water systems and reduces greenhouse gas emissions associated with the manufacture and transport of conventional agrochemicals [3]. In addition, NOCs promote long-term soil health by enhancing carbon sequestration and stabilizing soil organic matter, supporting humus formation and improved soil structure. These processes contribute to increased water-holding capacity, reduced erosion risk, and improved resilience of agroecosystems to climatic variability. At the ecosystem level, the use of NOCs has been associated with improved soil microbial diversity and activity, which underpin essential ecosystem services such as nutrient cycling and soil biological regulation. Beyond soil processes, NOC-based management practices support broader ecological functions, including pollinator activity, reduced non-target toxicity, and maintenance of trophic balance within agricultural landscapes. While these benefits are widely reported, their magnitude and persistence depend on site-specific factors, management intensity, and long-term adoption practices. Nevertheless, the ecological functions supported by NOCs align closely with global sustainability and climate-resilience objectives, reinforcing organic farming as a regenerative and low-impact production system [57,58].

5.6. Integration in organic farming systems.

Effective deployment of NOCs in organic farming systems requires an integrated management approach that combines plant-, animal-, microbial-, and mineral-based inputs to achieve balanced nutrient flows and functional synergy. Integrated application strategies—such as the combined use of compost enriched with humic substances and microbial inoculants—have been shown to improve soil fertility, plant health, and disease suppression more consistently than single-input approaches [13,30]. Advances in application methods, including foliar sprays, seed treatments, soil amendments, and fertigation systems, are increasingly optimized to improve bioavailability and reduce nutrient losses under organic management. However, successful integration of NOCs at the field scale depends on formulation stability, compatibility among inputs, and alignment with crop-specific growth stages. Variability in raw material quality and processing methods can further influence agronomic performance. From a practical perspective, broader adoption of integrated NOC-based strategies will require standardized formulations, robust field validation across

agroecological zones, and clear regulatory frameworks governing their production and use. Addressing these challenges is essential to ensure the scalability, economic feasibility, and consistent performance of NOCs, thereby enabling their reliable integration into sustainable, organic farming systems.

6. Challenges and Future Prospects

NOCs constitute one of the most promising domains in the transition toward ecologically balanced and resource-efficient agricultural systems. However, despite considerable scientific progress, multiple unresolved challenges continue to constrain their large-scale deployment, regulatory acceptance, and consistent performance within organic and sustainable farming frameworks. Addressing these constraints requires harmonized scientific, technological, and policy interventions supported by integrative research spanning chemistry, microbiology, agronomy, and systems ecology (Table 2).

Table 2. Key limitations hindering widespread NOC adoption in organic farming and corresponding multidisciplinary strategies to overcome them.

Identified challenge	Underlying limitation	Priority research or policy direction
Lack of standardization and quality control	High variability in biochemical composition due to source material, processing methods, and storage conditions; absence of universally accepted analytical benchmarks	Development of harmonized spectroscopic and chromatographic fingerprinting protocols coupled with functional bioactivity validation
Limited mechanistic understanding	Fragmented mechanistic evidence and limited integration of laboratory findings with field-scale performance	Integration of multi-omics approaches (metabolomics, transcriptomics, microbiome profiling) with long-term, replicated field trials
Formulation instability	Susceptibility of bioactive compounds to oxidation, volatilization, enzymatic degradation, and microbial contamination	Development of scalable, biodegradable encapsulation and controlled-release delivery systems with demonstrated environmental safety
Regulatory fragmentation	Divergent national and regional certification frameworks and unclear classification of biostimulants, biofertilizers, and organic amendments	Harmonization of regulatory and certification standards under FAO, IFOAM, and ISO guidance to support transparent approval and trade
Economic and adoption barriers	High production costs, inconsistent product performance, limited farmer awareness, and a lack of extension support	Cooperative production models, cost-benefit evaluation, farmer training programs, and policy-based incentives to support adoption

6.1. Standardization and quality assurance.

Perhaps the most persistent obstacle to reliable NOC application is the absence of standardized benchmarks for composition, bioactivity, and efficacy. Natural variability in source materials—driven by species identity, environmental growth conditions, processing methods, and storage parameters—results in pronounced fluctuations in biochemical profiles [18,19,59,60]. This heterogeneity undermines reproducibility and complicates regulatory validation. However, establishing uniform standards for biologically complex mixtures remains challenging, as single-marker quantification often fails to capture functional bioactivity. The development of harmonized chromatographic, spectroscopic, and metabolomic fingerprinting protocols offers a promising route toward chemical traceability and quality control, although their routine adoption remains limited outside research settings. Internationally aligned standards, analogous to those used in nutraceutical and pharmaceutical sectors, would substantially enhance credibility, comparability, and global trade of NOC-based products.

6.2. Mechanistic insights and field validation.

Although extensive laboratory and greenhouse studies demonstrate the biochemical and physiological effects of NOCs, translation to field-scale systems remains incomplete. Soil heterogeneity, climatic variability, crop genotype, and microbial community structure frequently modify compound stability and bioavailability, leading to inconsistent agronomic outcomes [13]. However, comprehensive long-term field trials remain scarce, and few studies integrate mechanistic insights with agronomic performance across multiple seasons. Multi-omics approaches—including metabolomics, transcriptomics, and metagenomics—hold strong potential for elucidating plant–microbe–soil feedbacks in situ [36], but their application remains limited by cost, data integration challenges, and the lack of standardized analytical pipelines. Long-term, replicated field experiments, combined with ecological modelling, will be essential to bridge the laboratory-to-field gap.

6.3. Formulation stability and delivery efficiency.

The physicochemical instability of many NOC formulations represents a major bottleneck for commercialization. Volatile or biologically active compounds—such as essential oils, peptides, and amino acid hydrolysates—are prone to oxidation, volatilization, polymerization, or microbial degradation during storage and transport [17]. However, advanced delivery strategies such as nanoencapsulation, alginate matrices, and biochar-based carriers often entail higher production costs and raise questions about environmental fate and regulatory approval. While controlled-release technologies show promise for extending shelf life and maintaining bioactivity, their scalability and long-term ecological safety require further validation. Future research should prioritize biodegradable carriers and adaptive formulations responsive to soil moisture or pH, balancing functional stability with environmental compatibility.

6.4. Integration with emerging technologies and climate resilience.

The convergence of NOCs with precision agriculture, digital monitoring tools, and climate-smart practices presents transformative opportunities. Artificial intelligence (AI) and machine-learning algorithms have demonstrated potential for optimizing application timing, dosage, and synergistic combinations tailored to specific soil–crop systems [3]. Remote sensing platforms and IoT-enabled sensors further enable real-time assessment of soil nutrient dynamics and plant physiological responses. However, most AI-assisted optimization frameworks remain at proof-of-concept or pilot stages, constrained by limited high-quality, standardized datasets for training and validation. In addition, access to digital infrastructure and technical expertise remains uneven across regions. While NOCs contribute meaningfully to climate resilience—through enhanced soil organic matter stabilization, reduced nitrous oxide emissions, and improved stress tolerance [18,38]—their integration into digital agriculture systems requires further technological maturation and cost–benefit evaluation.

6.5. Circular bioeconomy and sustainable production.

Valorization of agricultural and agro-industrial residues into NOCs aligns strongly with circular bioeconomy principles. Crop residues, fish-processing by-products, and municipal organic waste can be converted into humic-rich amendments and protein hydrolysates, reducing waste streams while generating value-added inputs [19,26]. However, variability in

feedstock quality, logistical constraints, and inconsistent processing efficiency pose challenges for producing standardized products at scale. Small-scale biorefineries and decentralized fermentation units offer promising socio-economic benefits, yet require coordinated quality control frameworks and economic incentives to ensure long-term viability. Bridging circular production models with agronomic performance remains a critical research and policy priority.

6.6. Policy frameworks, education, and global collaboration.

Regulatory fragmentation remains a major impediment to the global adoption of NOC-based bio-inputs. Biostimulants, biofertilizers, and organic amendments often fall under overlapping or ambiguous regulatory categories, delaying approval and discouraging innovation. However, regulatory acceptance typically favors validated, reproducible, and sometimes simpler inputs, meaning that conventional or low-complexity products may still be preferred in official protocols. Harmonization of standards under FAO, IFOAM, and ISO guidance would promote transparent certification and facilitate international trade [3]. Equally important are farmer education, extension services, and public–private partnerships to ensure appropriate application and sustained confidence in biologically complex products [32].

6.7. Outlook and research priorities.

The coming decade is likely to witness a transition from empirically driven application of NOCs to mechanistically informed, precision-guided deployment. Integrative research combining systems biology, advanced analytical chemistry, and environmental modelling will refine understanding of NOC-mediated soil–plant interactions. Bioinformatics and predictive analytics can further support the design of crop- and region-specific formulations. Overall, many of the approaches highlighted in this review remain at low-to-intermediate technology readiness levels for routine agricultural deployment. Careful validation, regulatory engagement, long-term field testing, and cost–benefit analysis will be essential to translate NOCs from experimental optimization tools into widely adopted, standardized components of sustainable and climate-resilient agriculture.

7. Conclusions

NOCs represent a critical component of sustainable and regenerative agricultural systems. Their multifunctional capacity to improve soil fertility, enhance nutrient cycling, stimulate plant growth, and mitigate biotic and abiotic stresses positions them as scientifically grounded alternatives to synthetic agrochemicals. By integrating plant-, animal-, microbial-, and mineral-derived compounds, organic farming systems can sustain productivity while preserving soil health and ecological integrity. The literature synthesized in this review demonstrates that NOCs exert their effects through interconnected biochemical, physiological, and ecological pathways involving nutrient mobilization, plant growth regulation, microbial mediation, and defence induction. These interactions collectively establish reinforcing feedback mechanisms that enhance system resilience and long-term agroecosystem stability, rather than acting through isolated or single-factor effects. Despite these advantages, widespread adoption of NOC-based products remains constrained by variability in source materials, insufficient standardization, limited long-term field validation, and fragmented regulatory frameworks. Addressing these barriers will require harmonized analytical standards, robust multi-season field trials, and coordinated policy support to ensure reproducibility,

efficacy, and farmer confidence. Interdisciplinary collaboration among chemists, microbiologists, agronomists, and policymakers will be essential to translate mechanistic understanding into reliable field-level solutions.

Looking forward, priority research directions should focus on integrating multi-omics approaches with precision agriculture tools to refine formulation design and application strategies. While emerging technologies such as artificial intelligence, advanced analytics, and nano-enabled delivery systems hold promise, many remain at early stages of adoption and must be evaluated through cost–benefit analysis, regulatory scrutiny, and ecological risk assessment. Aligning NOC development with circular bioeconomy principles by valorizing agricultural and industrial residues further strengthens their sustainability potential. Overall, natural organic compounds have the capacity to evolve from niche organic inputs into foundational components of climate-resilient and resource-efficient agricultural systems. Realizing this potential will depend on rigorous scientific validation, technological maturity, and coherent policy frameworks that support scalable, safe, and economically viable implementation.

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Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
NOCs	Natural Organic Compounds
VOCs	Volatile Organic Compounds
AI	Artificial Intelligence

Abbreviation	Definition
IPM	Integrated Pest Management
FAO	Food and Agriculture Organization
IFOAM	International Federation of Organic Agriculture Movements
ISO	International Organization for Standardization
SDGs	Sustainable Development Goals
IAA	Indole-3-Acetic Acid
ROS	Reactive Oxygen Species

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