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HUMIC ACID: INSIGHTS ON MAXIMIZING CROP YIELD, NUTRIENT USE EFFICIENCY AND SUSTAINING SOIL HEALTH

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ABSTRACT
The increasing demand for food production and the decline in soil fertility highlight the need for sustainable strategies to improve the crop productivity while maintaining soil health. Humic acid (HA) is a complex organic material formed during the decomposition and transformation of plant, animal and microbial residues. Its diverse functional groups and biological activity enable HA to influence soil properties, nutrient dynamics and plant growth. This review provides insights into the role of HA in maximizing crop yield, improving nutrient use efficiency (NUE), and sustaining soil health. The sources, formation, extraction protocols are discussed. Particular emphasis is given to its influence on soil physical, chemical and biological properties, including aggregation, water retention, cation exchange capacity, nutrient availability and microbial activity. The potential of HA to improve nitrogen, phosphorus and potassium use efficiency through enhanced nutrient retention, reduced losses, improved root development and nutrient uptake is also examined. Its effects on crop growth, yield and quality and its potential for mitigating soil degradation are summarized. However, HA effectiveness varies with its source, composition, application rate, formulation, soil properties, crop and environmental conditions. Therefore, standardization of HA products, optimized application strategies and long-term field evaluation are required. Overall, HA offers a promising approach for integrating crop productivity, efficient nutrient management and sustainable soil health.

KEYWORDS: Humic acid; Soil health; Crop yield; Nutrient use efficiency; Soil fertility; Plant growth; Soil degradation; Sustainable agriculture.

1. INTRODUCTION
Global agriculture must increase food production while maintaining the long-term quality of soil resources. Continuous cultivation, intensive tillage, unbalanced fertilizer use and insufficient return of organic residues can accelerate the loss of soil organic matter. Declining organic matter can affect soil structure, nutrient cycling, water storage and biological activity. These changes may reduce soil productivity and increase the dependence on external inputs. Therefore, maintaining soil organic matter and improving soil functions are important for sustainable crop production (Lal, 2020; Oldfield et al., 2019).

Humic acid (HA) is an important fraction of soil humic substances. It develops during the transformation and humification of plant, animal and microbial residues. HA contains several reactive functional groups, including carboxyl, phenolic and hydroxyl groups. These groups enable interactions with minerals, nutrient ions and other components of the soil environment. The chemical structure of humic substances also varies according to their origin and degree of humification (Lehmann & Kleber, 2015). Such structural characteristics allow HA to influence both soil processes and plant responses. The importance of HA is closely related to its ability to modify the soil environment. Humic substances can interact with soil minerals and contribute to aggregation, nutrient retention and water-related processes. Piccolo and Drosos (2025) emphasized that humified organic matter is closely associated with important soil functions, including fertility, water cycling and carbon storage. These functions are important for maintaining the capacity of soil to support crop growth over the long term. Thus, HA can be viewed not only as an organic amendment but also as a functional component of soil management. Improvement in the soil environment can create favourable conditions for root growth and crop development.

HA can influence root architecture, membrane activity and plant physiological processes. The interaction between humic substances and plant roots may stimulate root elongation and lateral root development, increasing the soil volume explored by the plant (Canellas et al., 2015). Better root development can improve access to water and nutrients and may consequently support biomass production and yield formation.

Crop productivity is strongly dependent on the availability and efficient use of essential nutrients. Fertilizer application does not always result in complete nutrient recovery by crops. Nutrients may be lost from the soil through leaching, volatilization, fixation, runoff and other transformation processes.

Improving nutrient use efficiency is therefore important for obtaining greater crop productivity from a given quantity of fertilizer. The use of organic amendments can help regulate nutrient dynamics by modifying the soil environment and nutrient retention processes (Said-Pullicino et al., 2007). The role of HA in nutrient management is particularly important because nitrogen, phosphorus and potassium behave differently in soil. Nitrogen is relatively mobile and can be lost through leaching and gaseous pathways. Phosphorus may become strongly retained by iron and aluminium minerals in acidic soils or associated with calcium compounds in alkaline soils. Potassium may be lost through leaching or become temporarily fixed within certain clay minerals.

Humic substances can interact with soil minerals and nutrient ions and thereby modify nutrient retention and availability (Gao et al., 2022). These interactions provide a possible basis for improving nutrient acquisition and utilization by crops. Nitrogen use efficiency is especially important because excessive nitrogen application can result in economic losses and environmental problems. Nitrogen recovery by crops is affected by the timing and amount of fertilizer application as well as soil and climatic conditions. Improving synchronization between nutrient supply and crop demand is therefore an important component of efficient fertilizer management (Congreves et al., 2021). HA may contribute to this process by modifying nitrogen retention, nutrient availability and root development. However, its effectiveness depends on the interaction between HA characteristics, soil conditions and fertilizer management. Phosphorus and potassium also require careful management because their availability is strongly controlled by soil properties. Phosphorus fixation can limit its movement towards plant roots, particularly in soils with high contents of iron, aluminium or calcium compounds.

Potassium availability is influenced by exchange reactions, leaching and clay mineralogy. Humic substances can modify these processes through their interactions with soil colloids and nutrient ions. Such effects may increase the proportion of nutrients available for plant uptake and improve the efficiency of fertilizer use (Sparks, 2003; Gérard, 2016). The influence of HA extends beyond nutrient availability to the broader concept of soil health. Healthy soil must maintain physical structure, chemical fertility and biological functioning at the same time. Humified organic matter contributes to these functions by supporting soil aggregation, carbon storage, nutrient cycling and water regulation. Piccolo and Drosos (2025) highlighted that soil health should be considered in relation to multiple soil functions rather than fertility alone. This broader perspective is particularly relevant for agricultural soils experiencing organic matter depletion and structural degradation. The interaction between HA, soil and plants therefore provides a potential link between crop productivity and long-term soil quality. Improved aggregation and water retention can favour root development. Better nutrient retention can reduce nutrient losses and increase nutrient availability. Changes in the rhizosphere environment can also influence microbial processes and nutrient cycling. These interconnected processes indicate that the value of HA should not be assessed only from changes in crop yield but also from its contribution to nutrient management and soil functioning.

However, the response to HA is not uniform across agricultural systems. Differences in source material, chemical composition, molecular characteristics and extraction procedures can influence its properties. Application rate, formulation and method of application can further modify its performance. Soil texture, pH, organic carbon, nutrient status, crop species and climatic conditions may also determine the magnitude of the response. Lehmann and Kleber (2015) emphasized the highly heterogeneous nature of humic matter, which helps explain why materials identified as humic substances can show different chemical and functional behaviour. Another important issue is the distinction between nutrient availability, nutrient uptake and nutrient use efficiency. An increase in soil nutrient availability does not necessarily result in greater plant uptake. Similarly, greater nutrient uptake does not always produce a proportional increase in yield. Nutrient use efficiency therefore needs to be evaluated by considering both nutrient recovery and crop productivity. This distinction is particularly important when assessing the contribution of HA to nitrogen, phosphorus and potassium management.

Thus, a comprehensive evaluation of HA requires consideration of its source and development, effects on soil properties, influence on crop growth and yield, and contribution to nutrient use efficiency. Its potential role in addressing soil degradation also needs to be considered together with application methods, limitations and practical constraints. Such an integrated assessment can help identify where HA provides meaningful benefits and where its response is dependent on specific soil, crop and environmental conditions. Therefore, this review provides an integrated assessment of humic acid as a potential strategy for maximizing crop yield, improving nutrient use efficiency and sustaining soil health.

The review discusses the sources and examines its effects on soil physical, chemical and biological properties. It further evaluates its influence on crop growth, yield and quality and its role in improving the use efficiency of nitrogen, phosphorus and potassium. In addition, the review considers the potential of HA for mitigating soil degradation, its major agricultural applications, current limitations and future research priorities. The overall objective is to identify effective and soil- and crop-specific strategies for integrating HA into sustainable and resilient agricultural production.

2. Sources of humic acid

Humic acids are heterogeneous organic compounds formed during the humification process, in which plant, animal and microbial residues undergo decomposition and transformation (Albrecht, 2019). They constitute the alkali-soluble and acid-insoluble fraction commonly found in soils, peat, freshwater systems and marine environments. Based on their solubility characteristics, humic substances are classified into three principal fractions: humic acid (HA), fulvic acid (FA), and humin (Pettit, 2004) (Didonato et al., 2016). The major sources of HA include leonardite, lignite, peat, soil organic matter, compost, vermicompost, animal manure, crop residues and agro-industrial wastes (Yakhin et al., 2017). The major natural, commercial and renewable sources of humic acid are illustrated in Fig.1.Among these, leonardite and lignite are important commercial sources because of their high content of humified organic carbon (Ertem et al., 2024). Leonardite, an oxidized form of lignite formed through the long-term geological transformation of organic matter, is one of the richest commercial sources of humic acid and is extensively utilized for the production of humic-based agricultural products (Karr, 2001). Peat is another naturally occurring source, formed from the gradual accumulation and decomposition of plant material under waterlogged conditions (Cameron et al., 1989).

Soil organic matter acts as a natural reservoir of humic substances, while compost and vermicompost provide humified organic matter through the transformation of biodegradable materials. Animal manure, crop residues and agro-industrial wastes are increasingly considered alternative sources because they can be processed into humic or humic-like substances, providing an opportunity to utilize locally available organic resources. The use of these alternative feedstocks can support organic waste recycling, carbon stabilization and circular nutrient management (Maffia et al., 2024). However, the characteristics and agronomic effectiveness of HA vary according to the source material, degree of humification, decomposition conditions, extraction procedure and chemical composition.

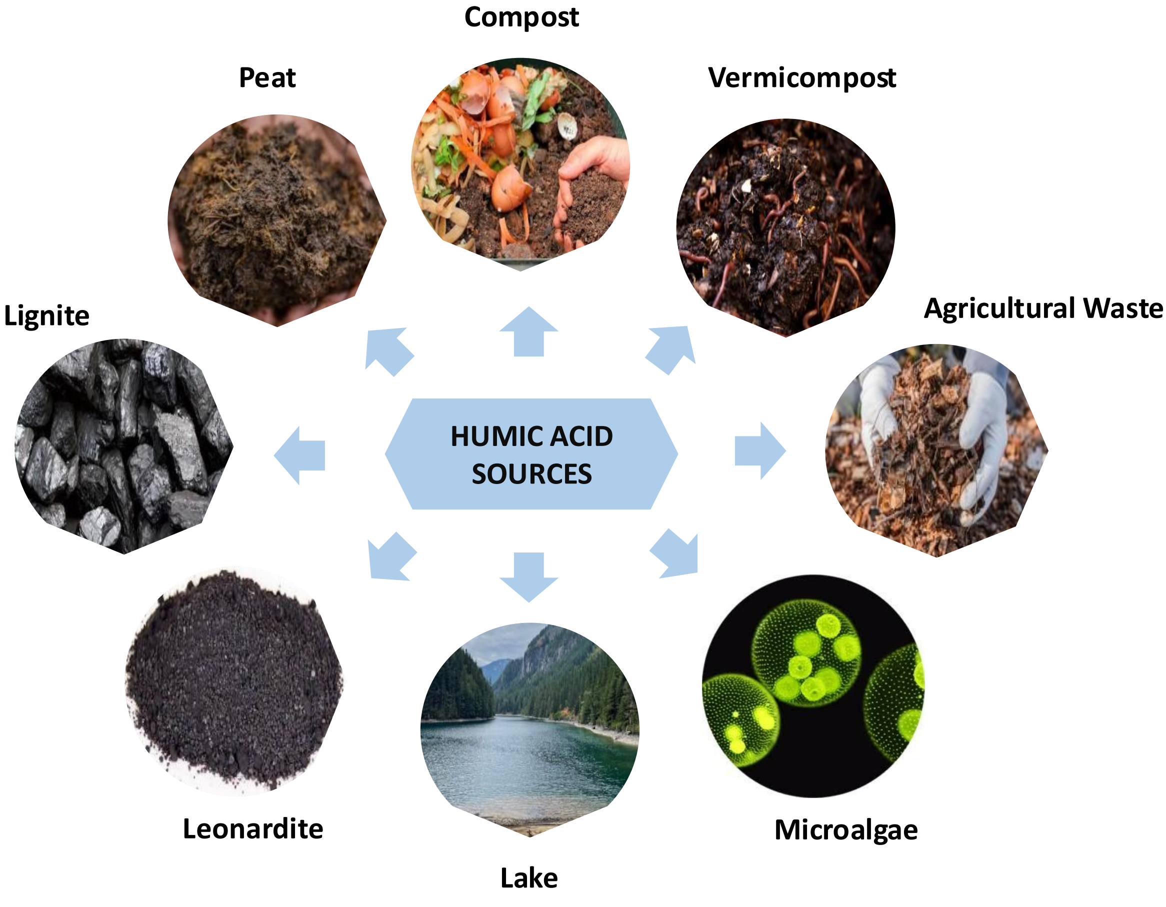

Fig. 1. Different sources of humic acid

3. Protocols in developing humic acid

The development and isolation of humic acid (HA) from natural organic matter rely primarily on alkaline extraction followed by acid precipitation, a methodology standardized by the International Humic Substances Society (IHSS) to ensure reproducibility and structural integrity (Chin et al., 2023). This protocol exploits the pH-dependent solubility of humic substances, where HA is soluble in alkaline conditions but precipitates under acidic conditions, allowing for its separation from fulvic acids and humin (Li et al., 2024; Jarukas et al., 2021). The efficiency and structural fidelity of the extracted HA are critically influenced by the choice of extractant, the nature of the raw material, and the specific process parameters employed during extraction (Allahkarami et al., 2025; Y. Yang et al., 2024).

3.1 Standard alkaline extraction and acid precipitation protocol
The foundational procedure for HA isolation involves treating organic-rich materials, such as peat, lignite, or soil, with an alkaline solution to dissolve the humic substances (Wu et al., 2024). Sodium hydroxide (NaOH) and potassium hydroxide (KOH) are the most commonly used extractants due to their strong basicity, which effectively breaks hydrogen bonds and ionizes acidic functional groups within the HA matrix (Jarukas et al., 2021b). Following extraction, the mixture is typically centrifuged or filtered to remove insoluble residues, primarily humin and mineral matter. The resulting supernatant, containing dissolved humic and fulvic acids, is then acidified to a pH of approximately 1–2 using strong acids like hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) (Li et al., 2024b). At this low pH, HA becomes protonated and insoluble, forming a precipitate that can be collected via centrifugation (Y. Yang et al., 2024b).
The precipitate is subsequently washed with dilute acid and deionized water to remove residual salts and impurities before being dried, often via freeze-drying to preserve its native structure (Radwan et al., 1997).

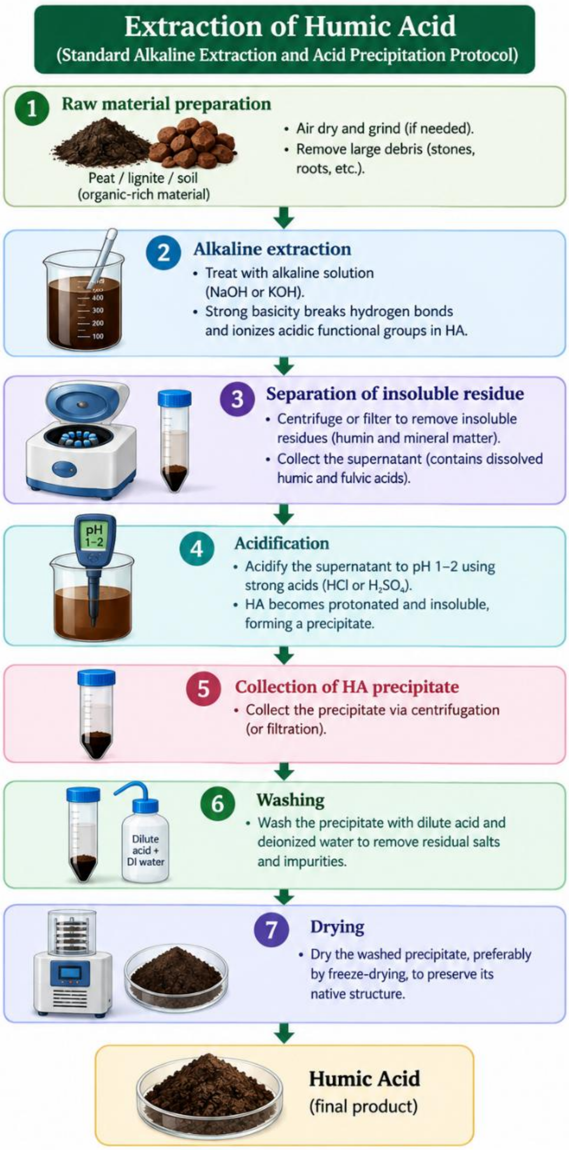

Fig. 2. Standard protocol for humic acid extraction

3.2 Emerging sustainable extraction technologies
Sustainability challenges in HA extraction have driven the development of greener and more efficient methods (Allahkarami et al., 2025b).Artificial humification technologies, such as hydrothermal treatment of lignocellulosic biomass (e.g., rice straw), offer a sustainable alternative to traditional mining of peat and coal (Wang et al., 2022).These methods simulate natural humification processes under controlled conditions, producing artificial HA with tailored properties for specific applications, such as slow-release fertilizers. Urea-assisted artificial

humification at room temperature has been demonstrated as an energy-efficient approach to producing water-soluble HA from agricultural waste, concurrently generating crude cellulose as a valuable byproduct. These innovations not only reduce environmental impacts but also expand the potential feedstocks for HA production, aligning with circular economy principles (Ore et al., 2023).

In conclusion, the protocol for developing humic acid involves a careful balance of extraction efficiency and structural preservation. While the standard alkaline extraction-acid precipitation method remains the cornerstone, optimization of extractants, process conditions, and source materials is essential for producing high-quality HA. Emerging sustainable technologies further enhance the viability of HA production, offering environmentally friendly alternatives to traditional methods. Rigorous characterization using spectroscopic and elemental analysis ensures the consistency and functionality of the final product, supporting its diverse applications in agriculture, environmental remediation, and industry.

4. Effects of humic acid on soil and crop performance

4.1 Humic acid and soil health improvement

Humic acid (HA) has the potential to improve the physical, chemical and biological properties of soil, thereby contributing to overall soil health and plant development. These effects include improvements in soil aggregation, relative particle distribution, water-holding capacity, cation exchange capacity (CEC), soil carbon content, enzyme activity, macronutrient cycling and nutrient availability (Ampong et al., 2022).

4.1.1 Effect of humic acid on soil physical properties

HA improves soil physical properties through its interactions with soil minerals, cations and soil organic matter. The functional groups such as - COOH and - OH present in HA facilitate its adsorption onto clay minerals and soil particles. HA can also complex with polyvalent cations such as Ca^{2+}, Mg^{2+} and Fe^{3+}, which act as bridges between HA and clay surfaces, promoting the formation of stable organo-mineral complexes. These interactions enhance the binding of individual soil particles and promote the formation of stable macroaggregates, resulting in increased mean weight diameter and aggregate stability. Humic substances have also been reported to improve aggregate stability and promote macroaggregate formation in sandy, saline–alkali, reclaimed and degraded soils (Ashokan et al., 2024; Kandra et al., 2024). Application of bentonite–humic acid increased macroaggregate formation in degraded sandy soil under 7 years of continuous maize cultivation (Zhou et al., 2019). Coal-derived humic acid also increased soil structural stability irrespective of soil type under controlled wetting–drying conditions (Piccolo et al., 1997). Humic fractions from manure and peat improved aggregate-size distribution, while artificial humic acid increased macroaggregates and mean weight diameter through enhanced fungal activity and binding agents (Fortún et al., 1990; Ai et al., 2023). In saline–alkali soil, humic acid combined with alkali residue produced maximum macroaggregate formation at approximately 3% application, mainly through Ca^{2+} mediated binding of humic substances with soil colloids (Liu et al., 2024).

The improvement in aggregate stability modifies soil pore-size distribution and connectivity, thereby increasing favourable pore spaces and reducing excessive compaction. Consequently, HA application can decrease soil bulk density, particularly in degraded and poorly structured soils, while improving total porosity. A combined amendment of humic acid, superabsorbent polymer and biochar reduced bulk density by approximately 24% and increased porosity by 27%, indicating that complementary amendments can enhance the physical benefits of humic acid (Li et al., 2020). In albic soil, modified humic acid mainly improved aggregate stability, whereas composite amendments were more effective in improving pore connectivity (Ling-Li et al., 2025).

The hydrophilic functional groups of HA, together with the improved pore structure, enhance soil water retention and plant-available water. Changes in aggregation and pore distribution can also regulate water movement through the soil, with the response of hydraulic conductivity depending on soil texture, HA source and application rate. In addition, HA-induced stimulation of fungal growth and microbial activity can contribute to aggregate stabilization, as fungal hyphae and microbial extracellular substances function as additional biological binding agents. HA application under continuous peanut cropping increased fungal abundance but decreased bacterial numbers, whereas its application in sweet-potato cultivation increased the populations of *Firmicutes* bacteria, *Basidiomycota* fungi and *Mortierellomycota* fungi (Li et al., 2019). These findings indicate that HA can influence microbial communities, and that the response varies with crop type, soil conditions and cropping history. Thus, HA-mediated improvement in aggregation, pore structure, water relations and microbial activity contributes to a more stable, less compact and physically favourable soil environment for plant growth.

4.1.2 Effect of humic acid on soil chemical properties

HA is an important component of soil organic matter. Its chemical effects are mainly attributed to its abundant functional groups, large surface area, negative charge, and ability to interact with soil minerals and nutrient ions. Through these properties, HA improves nutrient retention, modifies soil chemical conditions, and supports long-term soil fertility.One of the most important effects of HA is its influence on soil cation exchange capacity (CEC). The carboxyl (-COOH) and phenolic hydroxyl (-OH) groups present in HA provide negatively charged sites that can retain nutrient cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and ammonium (NH^{4+}). Consequently, HA can reduce nutrient leaching and improve the retention and availability of nutrients in the root zone. In a combined treatment involving organic fertilizer, montmorillonite, and HA, soil CEC increased by 41.07%, reaching 27.10 cmol kg^{-1} (Yang et al., 2024). Similarly, the addition of 1% HA to soilless substrates increased CEC in sand, cocopeat, and mixed growing media (Xu & Mohamed, 2021). Incubation of an Alfisol

with potassium humate also produced a significant increase in CEC up to an application rate of 40 kg HA ha^{-1} (M. et al., 2023). In acidic latosol, the application of an alkaline HA fertilizer increased CEC and reduced exchangeable aluminium by 56–67% (Deng et al., 2021).
Humic acid also contributes to the regulation of soil pH. Its functional groups can donate or accept protons depending on the surrounding soil conditions, allowing HA to buffer rapid changes in soil acidity or alkalinity. However, the direction and magnitude of the pH response depend on the source, chemical nature, application rate, and initial pH of the soil. In some cases, acidic HA formulations may slightly reduce soil pH, whereas alkaline humates may increase pH in acidic soils. Thus, HA generally helps stabilize the soil chemical environment rather than producing a uniform pH response.
Another important chemical function of HA is the chelation of micronutrients. Humic acid can form stable complexes with iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu). This process helps prevent the precipitation, fixation, or conversion of these elements into unavailable forms, particularly in alkaline and calcareous soils. As a result, the solubility and bioavailability of micronutrients may be improved, supporting balanced plant nutrition. Humic acid can also improve phosphorus availability, especially in acidic soils. In such soils, phosphate is commonly fixed by iron and aluminium oxides and becomes less available to plants. HA can interact with these metal ions and mineral surfaces, thereby reducing phosphate fixation and maintaining a greater proportion of phosphorus in plant-available forms. Its effects on phosphorus availability may also be associated with changes in soil pH, organic matter content, and microbial activity.
Through its interaction with soil minerals and nutrient ions, HA can improve nutrient retention and influence the cycling of nitrogen, phosphorus, potassium, and sulfur. These interactions may reduce nutrient losses and enhance the efficiency of applied fertilizers. In addition, HA contributes to soil carbon accumulation and stabilization, thereby supporting the maintenance of soil organic matter and long-term soil fertility (Ampong et al., 2022). Humic acid may further influence soil salinity and ionic balance. By increasing the soil's capacity to retain and exchange cations, it can contribute to salt buffering and help moderate the effects of excessive soluble salts. However, its effect on electrical conductivity (EC) depends on the composition and application rate of the HA product, as well as the quantity of accompanying soluble salts. Therefore, HA should not be assumed to increase or decrease EC uniformly under all soil conditions.
The application of HA can also affect soil redox reactions and the transformation of organic and inorganic forms of nitrogen, phosphorus, and sulfur. These changes are closely related to its role as a reactive form of soil organic matter and its interactions with minerals, metal ions, and microorganisms. For example, HA application under continuous peanut cultivation altered the soil microbial community by increasing fungal abundance while decreasing bacterial abundance (Li et al., 2019). This response may have been partly associated with changes in soil pH and nutrient availability, since many soil bacteria grow optimally at a pH near 6–7.Overall, humic acid improves soil chemical quality by increasing CEC, buffering pH fluctuations, enhancing nutrient retention, chelating micronutrients, reducing phosphorus fixation, modifying aluminium toxicity, and supporting nutrient and carbon cycling. These changes create a more favourable rhizosphere environment, improve the efficiency of fertilizer use, and contribute to sustainable soil fertility management. However, the magnitude and direction of its effects depend on soil type, initial chemical properties, HA source and composition, application rate, and environmental conditions.

4.1.3 Effect of humic acid on soil biological properties

HA consistently enhances soil biological properties by stimulating microbial biomass, increasing enzyme activities, and reshaping microbial community structure across diverse soil types and cropping systems (Zhou et al., 2024) (Ennan et al., 2022). These biological improvements are driven by HA's rich functional groups, which provide carbon sources and energy that facilitate microbial growth and alter metabolic activity (Zhang et al., 2026) (Guo et al., 2025) (Al-Malaky et al., 2024). HA application significantly increases soil microbial biomass and total microbial populations. In aeolian sandy soils, a single lignite HA application enhanced microbial biomass C and N four years post-treatment, with more pronounced effects at higher rates (Zhou et al., 2024b). Coastal Entisol rice paddies saw a 68.73% increase in total microbial population following HA addition (Wahyuni et al., 2023). HA also increased bacterial and fungal colony counts, actinomycetes, and microbial biomass nitrogen in black soil paddy fields under water-saving irrigation. However, one study in Lei bamboo plantations found that water-soluble HA fertilizer decreased microbial biomass carbon (MBC), likely because nondegradable carbon reduced SOC mineralization and microbial carbon utilization efficiency (Ni et al., 2024).
Humic acid application effectively modulates soil microbial community structure, promoting the proliferation of beneficial bacteria and fungi while suppressing pathogenic fungal populations. These shifts in microbial dynamics contribute significantly to enhanced soil physicochemical properties, enzymatic activity, and overall microbial diversity (Li et al., 2019).A study on humic acid-based biodegradable film in yam cultivation demonstrated that humic acid reshapes soil microbial communities by increasing the abundance and diversity of beneficial microorganisms—such as *Acidobacteriota*, *Myxococcota*, and *Proteobacteria* which play key roles in nutrient cycling and organic matter decomposition. This application also enhanced rhizosphere microbial activity and soil biochemical processes, thereby improving nutrient availability, soil health, and crop productivity (Lu et al., 2026). Artificial humic acid significantly reshaped soil microbial diversity, increasing humic acid content by 41.60% in soybean soil and 56.88% in paddy soil, while stimulating beneficial bacterial groups such as *Cyanobacteria*, *Chloroflexi*, and *Actinobacteriota*—organisms involved in carbon sequestration, organic matter decomposition, and humus synthesis. It also enhanced microbial metabolic pathways related to amino acid metabolism, carbon

cycling, and polyphenol biosynthesis, thereby improving soil fertility and microbially driven humification processes (Meng et al., 2026). The combined application of humic acid, mineral fertilizers, and phosphate-solubilizing bacteria improved vegetative growth and nutrient acquisition in pea plants, underscoring the role of humic acid in biofertilization practices (El-Sayed & El-Sayed, 2020). Humic substances promote microbial activity and nutrient uptake, reducing dependence on synthetic fertilizers and serving as a crucial component of sustainable agricultural practices. Through their dual function of enhancing nutrient availability and stimulating microbial dynamics (Li et al., 2019; Lu et al., 2026), humic acids serve as effective tools for improving soil health and increasing plant productivity (Chen & Aviad, 1990; Lumactud et al., 2022).

4.2 Humic acid and nutrient availability

Humic substances comprising humic acid, fulvic acid, and humin enhance nutrient bioavailability and soil fertility primarily through high cation exchange capacity, reactive functional groups, and the formation of organo-mineral complexes (Wang et al., 2024). In degraded soils, HS facilitate the restoration of nutrient equilibrium by mitigating losses due to leaching, fixation, erosion, and volatilization. HS optimize nutrient availability by increasing soil CEC, thereby improving cation retention and reducing leaching. Coal-derived HS have been shown to increase soil CEC more effectively than conventional organic amendments such as compost and manure (Yang et al., 2021). Humic acid improves nitrogen availability by stabilizing ammonium and providing organically bound nitrogen for microbial mineralization (Ampong et al., 2022); nitrogen uptake is further enhanced by low-molecular-weight HA and the presence of carboxylic functional groups (Tavares et al., 2019).

According to a recent study by Castro et al., 2021, the aliphatic and aromatic functional groups of HA increased soluble sugars and N uptake, which in turn increased rice yield**.** Consequently, HA application consistently improves crop yield, nitrogen uptake, and nitrogen use efficiency (Ma et al., 2024).Beyond nitrogen, HS facilitate phosphorus availability by attenuating P fixation and promoting solubilization. HA and FA stimulate microbial phosphatase activity, accelerating the release of plant-available phosphorus (Sharma et al., 2013), while HA reduces phosphate sorption and enhances desorption, increasing phosphorus concentrations in the soil solution (Zhu et al., 2017).Micronutrient bioavailability is similarly optimized through the chelating and complexing properties of HS. HA forms stable complexes with nutrients like Fe, Zn, Mn, and Cu, facilitating their transport and uptake (Sible et al., 2021; Yang & Antonietti, 2020; Zanin et al., 2019) . Furthermore, HS increase plasma membrane permeability, directly enhancing root nutrient absorption (Nardi et al., 2002). However, effects vary by soil condition (Yang et al., 2021); for instance, FA increases Mn availability in calcareous soils, whereas HA may reduce Cu availability through strong complexation (Barzgar et al., 2025).

HS also stimulate microbial activity and nutrient cycling. They regulate interactions between soil microorganisms and nutrient-based nano agrochemicals, thereby preserving microbial-mediated nutrient transformations and improving nutrient use efficiency (González-Feijóo et al., 2026). Artificial humic and fulvic acids enhance soil humification, microbial biomass, and enzymatic activities involved in nutrient cycling (Meng et al., 2025). Additionally, HA mitigates nutrient fixation and leaching, increasing the availability of N, P, K, Fe, Zn, and Mn (Antu et al., 2025). In maize, HA application has been shown to increase N, P, and K uptake through synergistic improvements in root growth and soil nutrient availability (Sharif et al., 2002).In conclusion, humic substances act as essential regulators of nutrient cycling by bolstering nutrient retention, bioavailability, and plant uptake. Their capacity to enhance nutrient use efficiency makes them valuable amendments for restoring fertility and productivity in degraded soils.

4.3 Humic acid and nutrient use efficiency

Nutrient use efficiency (NUE) refers to the ability of crops to absorb, utilize and convert applied nutrients into economic yield. Humic acid (HA) improves nutrient use efficiency through its influence on nutrient retention, nutrient availability, root development and plant nutrient metabolism. The efficiency of HA depends on its source, chemical characteristics, application rate, soil properties, crop species and method of application.Humic acid contains several reactive functional groups, particularly carboxyl and phenolic groups, which interact with soil minerals and nutrient ions. These interactions can improve the retention of ammonium and influence the availability of phosphorus and micronutrients. In addition, HA may improve soil aggregation, moisture retention and root-zone conditions, thereby facilitating nutrient acquisition by plants. Its hormone-like activity can stimulate root elongation, lateral root formation and root hair development, increasing the root surface area available for nutrient absorption.

4.3.1 Nitrogen use efficiency

Humic acid (HA) improves nitrogen use efficiency through its combined effects on nitrogen retention, fertilizer nitrogen release, root development and plant nitrogen metabolism. The process begins with the interaction of HA functional groups, particularly carboxyl and phenolic groups, with soil minerals and nutrient ions. These interactions influence ammonium retention and nitrogen mobility in the soil, thereby potentially reducing nutrient losses. When applied with urea, HA may regulate urea hydrolysis and nitrogen release, reducing the rapid accumulation of ammonia and subsequent ammonia volatilization. Liu et al. (2019) demonstrated that humic acid extracted from sludge fermentation liquid inhibited urease activity and prolonged the release of ammonia nitrogen, suggesting a possible mechanism for regulating urea decomposition. In a maize - wheat rotation system, Kong et al. (2022) reported that humic acid urea reduced nitrogen losses through leaching, ammonia volatilization and nitrous oxide emission by 25.51%, 23.07% and 23.08%, respectively, compared with conventional urea. These findings indicate that HA-based nitrogen fertilizers can reduce nitrogen losses and improve the retention of fertilizer-derived nitrogen under suitable conditions.

In addition to reducing nitrogen losses, HA may enhance nitrogen uptake by promoting root development and regulating nutrient transport. Humic substances exhibit hormone-like activity and can stimulate lateral root formation, root elongation and root hair development, thereby increasing the root surface area available for nutrient absorption. They may also activate plasma membrane H^+-ATPase, which generates the electrochemical gradient required for the transport of mineral nutrients across root cell membranes. Nardi et al. (2021) described the role of humic substances in regulating root growth, nutrient transporters, plasma membrane H^+- ATPases and enzymes involved in nitrogen assimilation. Enhanced root activity and nutrient transport can increase the plant's capacity to absorb available nitrogen from the soil. Following nitrogen uptake, HA may influence nitrogen assimilation and plant metabolism by affecting nitrate reduction and the incorporation of inorganic nitrogen into organic compounds. Enzymes such as nitrate reductase, glutamine synthetase and glutamate synthase play important roles in the conversion of absorbed nitrogen into amino acids and proteins. Improved nitrogen assimilation can support chlorophyll formation, photosynthetic activity and biomass production. However, the response of these enzymes depends on the humic substance source, application rate, crop species and nutritional conditions.

Humic acid may also improve the synchronization between nitrogen supply and crop demand by regulating fertilizer nitrogen release and improving nutrient retention in the root zone. Guo et al. (2022) reported that the addition of humic acid to controlled-release fertilizer increased nitrogen use efficiency by 4.6–5.4% compared with controlled-release fertilizer alone and reduced annual nitrous oxide emissions by 29%. Furthermore, a meta-analysis by Ma et al. (2024) showed that humic acid application increased crop yield, nitrogen use efficiency and nitrogen uptake by 12%, 27% and 17%, respectively, on average. Thus, humic acid can improve nitrogen use efficiency through a combination of reduced nitrogen losses, enhanced root uptake, improved nitrogen assimilation and better synchronization of nitrogen supply with crop demand. Nevertheless, these effects are dependent on soil properties, fertilizer formulation, humic acid characteristics and crop management practices.

4.3.2 Phosphorus use efficiency

Phosphorus (P) use efficiency is generally low because phosphorus is strongly fixed or precipitated in the soil and moves very slowly towards plant roots. In acidic soils, P is mainly fixed by iron (Fe) and aluminium (Al), whereas in alkaline and calcareous soils, it can precipitate with calcium (Ca). Therefore, improving the availability and movement of P in the soil is essential for increasing phosphorus use efficiency. Humic acid (HA) can improve P use efficiency by reducing P fixation, increasing P availability around the root zone and promoting plant P uptake. The main mechanism begins with the interaction of HA with Fe, Al and Ca present in the soil. The carboxyl and phenolic groups of HA can bind with these metal ions and modify their interaction with phosphate. HA can also compete with phosphate for adsorption sites on soil minerals. As a result, less phosphate may become strongly fixed, while more P remains available for plant uptake. HA can therefore increase the soluble and plant-available forms of phosphorus in the rhizosphere. This effect is particularly important in soils where P fixation is high.

HA also improves P acquisition by promoting root development. Since phosphorus moves through soil mainly by diffusion, its availability to plants depends strongly on the contact between roots and P-containing soil. HA-induced increases in root length, lateral roots and root hairs can increase the volume of soil explored by the plant and consequently improve P absorption. In addition, HA may stimulate phosphatase activity and other biological processes that convert organic or poorly available P into forms that can be taken up by plants. HA-induced changes in root exudation and microbial activity may further contribute to P mobilization in the rhizosphere.

The beneficial effect of HA on P use efficiency has been demonstrated in several crops. Haider et al. (2026) reported that HA application to potato grown under saline conditions increased phosphorus uptake efficiency by approximately 2.8-fold compared with the untreated control. Similarly, Jing et al. (2022) reported that HA-modified phosphate fertilizer increased P uptake in maize by 9.6–35.1% at lower HA concentrations of 2.5–5 mg C L^{-1}. However, higher HA concentrations negatively affected nutrient absorption, indicating that the response depends on the application rate. The combination of HA with phosphate fertilizers can further improve P utilization. Zhang et al. (2024) reported that co-application of HA with coated diammonium phosphate reduced available phosphorus leaching by 49–63% and increased wheat grain yield by 17.2% compared with the corresponding fertilizer treatment. This indicates that HA can help retain P within the soil–root zone and improve its availability to crops. In acidic paddy soil, Hartina et al. (2025) found that HA application alone resulted in the highest phosphorus use efficiency and phosphorus agronomic efficiency, whereas combining HA with gypsum did not provide additional improvement. This suggests that the effectiveness of HA depends on soil conditions and its interaction with other amendments.

The improved P availability and uptake ultimately enhance phosphorus utilization within the plant. Phosphorus is essential for ATP formation, energy transfer, nucleic acid synthesis, membrane development and reproductive growth. Therefore, improved P acquisition can support photosynthesis, biomass production and grain or tuber development. Selladurai and Purakayastha (2016) reported that a humic acid-based multi nutrient fertilizer increased P use efficiency in potato by 9.3% compared with chemical fertilizer, while also improving N and K use efficiencies by 16.4% and 18.3%, respectively.

4.3.3 Potassium use efficiency

Potassium (K) is an essential macronutrient involved in enzyme activation, osmotic regulation, stomatal movement, water balance and photosynthesis. Unlike nitrogen, K does not undergo significant volatilization;

however, applied K may be lost through leaching in sandy and low-cation-exchange-capacity (CEC) soils or become temporarily unavailable through fixation within the interlayers of 2:1 clay minerals such as illite and vermiculite. Therefore, improving K retention and maintaining an adequate supply of plant-available K in the root zone are important for increasing potassium use efficiency (KUE).HA can improve KUE by modifying soil K retention and availability. The negatively charged carboxyl and phenolic functional groups of HA increase the number of exchange sites capable of retaining K^+, thereby contributing to greater K adsorption and reduced K movement below the root zone. HA addition has been reported to increase total K adsorption and the proportion of exchangeable K, which represents an important plant-available K pool. HA–K interactions may also regulate the release of applied K and maintain K availability in the rhizosphere. Thus, HA can improve the synchronization between soil K supply and crop demand, particularly in coarse-textured and low-CEC soils.

HA may further influence K dynamics in clay-rich soils by modifying interactions among clay minerals, organic matter and exchangeable cations. Potassium can become fixed between layers of certain 2:1 clay minerals, reducing its immediate availability to plants. The interaction of HA with clay surfaces and soil cations may modify K fixation–release processes and influence the proportion of K maintained in exchangeable or solution forms. However, this response is strongly dependent on clay mineralogy, soil pH, moisture conditions and initial K status and should therefore not be considered universal.

In addition to improving soil K availability, HA can enhance plant K acquisition by stimulating root development. Increased root length, lateral root formation and root hair development expand the volume of soil explored by roots and increase contact with available K. Humic substances may also influence cell membrane properties and plasma membrane H^+-ATPase activity, supporting ion transport and K^+ uptake. Consequently, HA-mediated improvement in root growth and membrane activity can increase K absorption and improve nutrient acquisition even when changes in soil-available K are relatively small. The improvement in K uptake can subsequently support physiological processes such as enzyme activation, photosynthesis, osmotic regulation and stomatal control. This is particularly important under drought and salinity, where adequate K helps maintain cellular osmotic balance and water relations. Under saline conditions, potassium humate has also been reported to improve K^+ uptake and reduce Na^+ accumulation, contributing to a more favourable K^+/Na^+ balance and improved plant performance.

Several studies have demonstrated the potential of HA-based treatments to improve K utilization. Ding et al. (2021) reported that combined application of 40 kg HA ha^{-1} with potassium-solubilizing bacteria (PSB) produced a maximum KUE of 40% in faba bean, compared with 14% under full mineral K fertilization alone. The combined treatment also allowed mineral K application to be reduced to 50% of the recommended rate while maintaining improved crop performance. Similarly, Selladurai and Purakayastha (2016) reported an 18.3% increase in KUE in potato with the humic-acid-based multi nutrient fertilizer Grow Flow 45H compared with conventional chemical fertilizer. The treatment also increased N and P use efficiencies by 16.4% and 9.3%, respectively, demonstrating the potential of humic-based fertilization for improving overall nutrient-use efficiency. The interaction between HA and K can also influence crop productivity and nutrient allocation.

Combined K and HA application has been reported to maximize garlic yield, photosynthetic pigments and nutrient allocation, with a moderate K_{120} + HA_{10} treatment producing the best response. Similarly, application of HA with 80% of the recommended NPK rate, together with foliar HA application, improved wheat productivity, nutrient uptake and economic returns to levels comparable with full fertilization (Alharby et al., 2026). These findings suggest that appropriate HA application may improve nutrient utilization and potentially permit partial reduction of mineral fertilizer inputs without substantial yield penalties.

However, the response to HA is strongly dose dependent. In maize seedlings, HA at 20 mg C L^{-1} resulted in maximum K uptake, whereas increasing the concentration to 50 mg C L^{-1} inhibited K absorption (Jing et al., 2020). Similarly, excessive HA application may reduce nutrient availability when strong interactions between HA functional groups and nutrients alter their mobility or accessibility to roots. In saline–alkali wheat systems, HA application increased soil available K by approximately 22–45%, with 7.5 Mg ha^{-1} identified as the optimum application rate. Therefore, increasing HA concentration does not necessarily produce a proportional increase in K availability or KUE, and excessive application may result in diminishing returns.

The effectiveness of HA in improving KUE is therefore governed by multiple interacting factors, including HA source, molecular characteristics, application rate, application method, soil texture, CEC, clay mineralogy, initial K availability and crop species. Ampong et al. (2022) emphasized that the relationship between HA-induced changes in soil K availability and subsequent plant K uptake remains insufficiently characterized. Earlier work has also suggested that excessive HA application should be avoided because nutrient-use responses may decline beyond an optimum dose. Therefore, HA should be applied at an appropriate rate rather than assuming that higher application rates will always improve K utilization.

Thus, HA has considerable potential to improve KUE by integrating soil K retention, regulated K availability, enhanced root acquisition and efficient plant utilization. Future research should focus on identifying crop- and soil-specific HA × K combinations and clarifying the mechanisms governing K adsorption, fixation–release, root uptake and utilization under contrasting soil and environmental conditions.

4.3.4 Micronutrient use efficiency.

Humic acid can influence the availability and uptake of micronutrients such as iron, zinc, manganese and copper through complexation and changes in soil chemical conditions. Its functional groups may bind micronutrient ions and modify their mobility and retention in the rhizosphere. Improved root development and microbial activity may further contribute to micronutrient acquisition. However, the effect of HA on micronutrient availability is nutrient-specific and depends on soil pH, mineral composition and the stability of metal–humic complexes.

Overall, humic acid has the potential to improve nutrient use efficiency through the combined effects of nutrient retention, regulated fertilizer release, enhanced root development and improved nutrient assimilation. The integration of HA with balanced fertilizer application and appropriate nutrient management may contribute to improved crop productivity and reduced nutrient losses. Nevertheless, further research is required to establish nutrient-specific mechanisms and standardized application rates under diverse soil and cropping conditions.

4.4 Humic acid and crop growth and productivity

Humic acid (HA) plays an important role in promoting crop growth and productivity by improving soil conditions, nutrient availability and plant physiological processes. Its application can influence root development, nutrient uptake, photosynthetic activity and overall plant growth, thereby contributing to improved crop establishment and yield formation

Table 1 Impact of Humic Substances on Crop Productivity.

Crop	HS Type/Source	Yield Response	Quality Response	Reference
Tomato (Solanum lycopersicum)	Straw-derived fulvic acid	↑ Fruit yield by 35%; ↑ fruit number by 44.4%	↑ Ca, Fe, Zn, amino acids, citric acid and malic acid	Zhang et al. (2021)
Lemon (Citrus limon)	Water-soluble humic acid, fulvic acid potassium and fulvic acid distillate	↑ Fruit weight, edible rate and juice yield	↑ Vitamin C, TSS, sugars, flavonoids, phenolics and antioxidants	He et al. (2022)
Wheat (Triticum aestivum)	Humic acid (4%)	↑ Grain yield (5.21 t ha^{-1}), biological yield, straw yield and harvest index	↑ Protein, starch, gluten, N, P and K contents	Lamlom et al. (2023)
Barley (Hordeum vulgare)	Humic acid + fulvic acid + P fertilizer	↑ Grain yield by 44–65%; ↑ straw yield and harvest index	↑ N, P and K uptake	Alsudays et al. (2024)
Rice (Oryza sativa)	Humic acid	↑ Grain yield by 5.75–6.0%	↑ Protein (11.9–13.4%) and starch (90–93%)	Kadam et al. (2024)
Triticale (×Triticosecale)	Humic acid + fulvic acid	↑ Grain yield, forage yield and 1000-grain weight	↑ Protein and carbohydrate content	Mosaad et al. (2024)
Maize (Zea mays)	Humic acid + fulvic acid	↑ Grain yield up to 8.09 t ha^{-1}; ↑ 1000-grain weight (379.9 g)	↑ Protein (9.11%) and oil content (5.32%)	Leiby et al. (2025)

4.5 Humic acid in mitigating soil degradation

4.5.1 Salinity stress

Soil salinization is a pervasive form of degradation that severely impairs soil structure, limits nutrient availability, suppresses microbial activity, and diminishes crop productivity (Abd-Elzaher et al., 2022; Huang, 2022). Humic substances have emerged as effective amendments for mitigating salinity stress and restoring the quality of salt-affected soils (Mosa et al., 2020) . Coastal soils, in particular, are frequently subject to salinization, a process that degrades soil structure, exacerbates nutrient leaching, and depletes soil organic matter (Zhao et al., 2025).The application of HA and biochar, known to increase soil water content while reducing salinity and pH (Khaled & Fawy, 2011; Sun et al., 2020).Organic matter-rich amendments, such as HA and AA, increase soil water content by promoting soil aggregation and water retention, which reduces water loss through evaporation and drainage and mitigates salt stress. Furthermore, the acidic organic components in these amendments help neutralize free OH^{-} ions, thereby improving the soil microenvironment.

The combined application of humic acid and attapulgite significantly improved the quality of coastal saline-alkali soils by reducing salinity and exchangeable sodium levels while enhancing soil moisture retention, cation exchange capacity, nutrient availability, and soil organic carbon content. These improvements promoted soil aggregation and nutrient retention, demonstrating the potential of humic substances to ameliorate saline soils through improved soil structure, nutrient retention, and salt leaching, thereby restoring degraded saline soils (Zhao et al., 2025).Humic acids possess numerous acidic functional groups. In alkaline saline soils, these groups dissociate and release negative charges, which bind with cations such as Na^+, thereby reducing the salt concentration around plant roots. The study further found that humic acids react with carbonate and bicarbonate salts commonly present in saline-sodic soils. This reaction releases carbon dioxide and helps neutralize alkalinity, thereby lowering soil pH and improving soil conditions (Moro et al., 2025).Numerous studies have demonstrated the efficacy of humic substances in mitigating salinity stress and restoring the quality of salt-affected soils through enhancements in soil physical properties, nutrient dynamics, microbial activity, and crop productivity. Key research findings are summarized in Table 2.

Table 2 Influence of Humic Substances on Saline Soil Reclamation and Crop Productivity

Source of HS	Soil/ Crop Type	Dose/Rate	Major Effects on Salinity	Reference
Potassium humate (K-humate)	Sandy saline soil / Wheat	10 and 20 kg ha^{-1}	Increased nutrient availability, K^+/Na^+ ratio, and wheat yield	(Abd-Elzaher et al., 2022)
BLACKJAK® (humic substances)	Lettuce under 100 mM NaCl	Root: 0.40–0.60 mL L^{-1}; Foliar: 7.50–10.00 mL L^{-1}	Improved growth, photosynthesis, and salt tolerance	(Atero-Calvo et al., 2024)
Humic acid	Salt-stressed rice	Seed priming with 40 mg L^{-1}	Improved growth and reduced salinity damage	(Shukry et al., 2023)
Humic acid soil modifier	Saline-alkali soil / Rice	Field application	Reduced salinity and increased rice yield	(Pang et al., 2023)
Humic acid (HA)	Saline-alkali soil / Maize	HA + chemical fertilizer	Reduced salinity and increased maize yield	(Wang et al., 2023)
Bio-humic acid soil amendment	Saline-alkali soil / Rice	3000 kg ha^{-1}	Reduced soil pH and increased rice yield	(Zhang et al., 2024)
Humic acid	Saline soil / Sweet pepper	25 and 50 kg ha^{-1}	Improved plant growth under saline irrigation	(Al-Kubissi et al., 2024)
Humic acid	Salt-stressed pittosporum	Foliar spray of 150 mg L^{-1}	Improved growth and K uptake	(Lasheen et al., 2023)

4.5.2 Heavy metal toxicity

Humic substances act as natural chelators that bind to heavy metals, forming stable organo-mineral complexes that effectively immobilize contaminants and reduce their bioavailability in soil and water systems (Wang et al., 2024).For instance, humic acid-modified coal gangue removed over 99% of Zn, Cu, and Pb from contaminated runoff and simultaneously improved plant growth, microbial diversity, and tolerance to heavy metal stress(Zhang et al., 2025).Straw-derived humic substances, particularly those produced under aerobic conditions, exhibited strong heavy metal detoxification potential by forming stable complexes with toxic metals through phenolic and

carboxylic functional groups, achieving removal efficiencies of up to 96.18% for Cd and substantially reducing the bioavailability of Cu, Zn, and Pb in contaminated soils(Zhong et al., 2023).
The combined application of humic acid and hydroxyapatite effectively detoxified cadmium-contaminated soil by reducing Cd bioavailability through complexation and immobilization processes. The treatment also enhanced beneficial microbial communities, decreased Cd accumulation in wheat grains, and improved crop productivity (Lu et al., 2025).
The study showed that humic substances, particularly fulvic acids, influence the sorption and immobilization of Cd and Pb in soils. Increased humification and structural stability of humic substances reduced the bioavailability of heavy metals, highlighting their important role in heavy metal detoxification and soil remediation.(Feszterová et al., 2024).The humic substances can remediate heavy metal-contaminated soils by acting as natural biosurfactants and complexing agents. The carboxyl and phenolic groups present in humic substances bind with heavy metal ions, forming soluble complexes that can be washed out of the soil. By mobilizing and removing toxic metals, humic substances reduce the overall heavy metal burden in contaminated soils. The study also showed that after humic substance washing, the remaining metals became more accessible for further remediation methods such as phytoextraction (removal by plants)(Piccolo et al., 2019).

4.5.3 Soil organic carbon depletion and restoration:

Soil organic carbon (SOC) depletion, driven by intensive cultivation, excessive tillage, residue removal, erosion, and insufficient organic matter inputs, represents a significant form of soil degradation. This decline adversely affects essential parameters—such as soil fertility, nutrient cycling, aggregate stability, water-holding capacity, and microbial activity—ultimately compromising soil productivity and ecosystem sustainability (Lal, 2015).SOC is a fundamental pillar of soil fertility and quality, acting as a pivotal element for terrestrial ecosystems with significant implications for food security and agricultural sustainability (Amanullah & Khan, 2024). By enhancing soil structure, aggregate stability, and nutrient retention, SOC supports superior crop growth, efficient nutrient cycling, and robust ecosystem functioning. Consequently, restoring SOC levels is an essential strategy for maintaining soil health and ensuring sustainable agricultural production (Cambronero et al., 2025).
Humic substances represent the most stable and significant fraction of soil organic carbon, playing a central role in preventing SOC depletion and restoring degraded soils (Maffia et al., 2025). As carbon stabilizers, structural binders, and biological regulators, HS constitute 50-80% of SOC, forming the most microbially resistant pool of soil organic matter. By shielding labile molecules from decomposition, HS mitigate mineralization and facilitate long-term carbon storage (Gerke, 2021; Sun et al., 2022). Their persistence relies heavily on hydrophobic and aromatic domains, which provide "hydrophobic protection". Furthermore, applications of artificial humic and fulvic acids can enhance total organic carbon beyond direct additions by promoting microbially amplified sequestration and stimulating CO_2-fixing microbes (Lan et al., 2024; Tang et al., 2021).
Humic molecules bind metals and other substrates, forming stable organo-mineral associations that immobilize carbon. Humic substances also strongly bind toxic metals and influence nutrient availability, consistent with their role in maintaining stable SOC (Gerke, 2022). Furthermore, the increased hydrophobic character of humic matter reduces microbial access to labile inputs, thereby limiting mineralization. Research indicates that root cellulose and root-derived carbon preferentially contribute to fulvic acid formation, which serves as a significant driver of SOC accumulation during grassland revegetation and restoration processes (Bai et al., 2020).Microbial synthesis of HS from residues (e.g., coir pith) can accelerate humification and enhance soil C sequestration capacity (Muniraj et al., 2021).Long-term alfalfa revegetation on semiarid abandoned farmland significantly enhances soil organic carbon sequestration compared to natural fallow. This accumulation is driven by intensified humification—notably higher humic acid and humin levels—and the promotion of stable soil micro-aggregates that protect carbon from decomposition.
These findings underscore the critical role of humic substances and aggregate formation in long-term carbon storage and effective ecological restoration strategies (Song et al., 2024).Thus, integrating humic substance-based approaches into soil management practices offers a promising pathway for rebuilding SOC stocks in degraded landscapes.

4.5.4 Soil erosion and aggregation

Soil erosion accelerates the degradation of soil structure by disrupting aggregates and removing organic carbon-rich surface layers. Because a substantial proportion of soil organic carbon is stored within macroaggregates, their breakdown during erosion leads to significant carbon losses. Humic substances enhance aggregate stability through their amphiphilic properties, promoting the formation of water-stable aggregates and improving soil resistance to erosion. In particular, labile humic substances associated with microaggregates play a crucial role in maintaining structural integrity. Therefore, the content of labile humic substances within soil aggregates can serve as an indicator of soil aggregation and erosion resistance (Gromovik et al., 2023).Humic substances act as soil conditioners that reinforce the soil surface structure, allowing it to withstand heavy rainfall while significantly reducing water and sediment losses from the field (SİNKPEHOUN & Yönter, 2018). Increased soil aggregation facilitated by humic substances enhances erosion resistance, as stable aggregates are less susceptible to disintegration under erosive forces.

According to (Hayes & Roulia, 2025), humic substances enhance soil erosion resistance by promoting the formation of stable organo-mineral aggregates that improve soil structural integrity and protect organic carbon from erosive losses. Furthermore, studies indicate that specific forest management practices can enhance the positive effects of humic substances on soil stability, thereby reducing erosion risks (Meng et al., 2022).The role of humic substances in erosion control has also been demonstrated through their effects on soil mechanical properties. The incorporation of humic substances increased aggregate stability and soil tensile strength through the formation of stable cementing structures, resulting in greater resistance to particle detachment and erosion over time (Miranda et al., 2020).

Similarly, humic acid combined with polyacrylamide copolymers enhanced soil structural stability, increased soil strength, and effectively reduced simulated wind and water erosion, demonstrating its potential as an environmentally friendly soil stabilizer for erosion control and land restoration (Bekturganova & Mirzaeian, 2025).However, the influence of humic substances on erosion-related nutrient dynamics may vary depending on soil mineralogy. Humic acid can influence soil erosion-induced nutrient losses by competing with phosphorus for adsorption on clay minerals, particularly kaolinite, thereby increasing phosphorus mobilization and transport in runoff (Chen et al., 2022).Collectively, these findings underscore the essential role of humic substances in bolstering soil aggregation and mitigating erosion susceptibility, positioning them as critical components in soil restoration and conservation strategies.

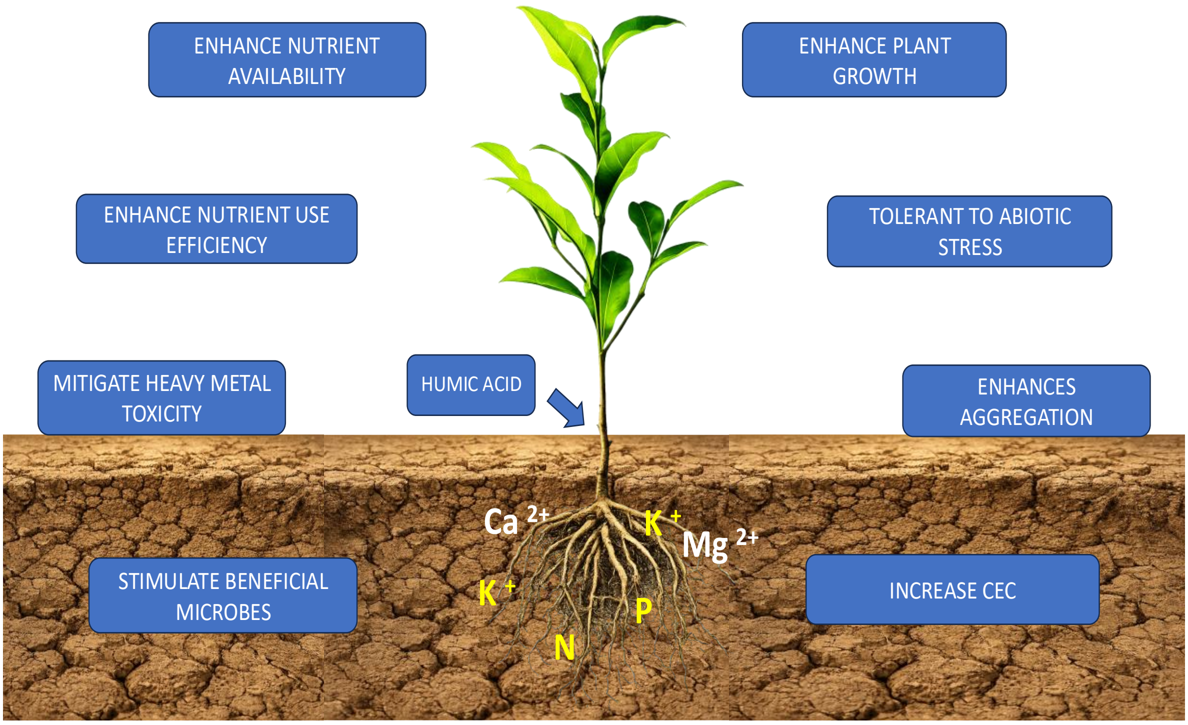

Fig. 3. Multifunctional role of humic acid

5. Limitations and challenges

Humic acid research and application face several notable limitations and challenges that constrain its widespread adoption and consistent efficacy in agricultural systems. One of the foremost challenges lies in the variability of humic acid sources and extraction methods, as humic substances derived from different raw materials such as leonardite, peat, compost, or lignite exhibit significant differences in molecular structure, functional group composition, and biological activity, making it difficult to standardize products or compare results across studies. This heterogeneity is compounded by the lack of

universally accepted protocols for characterizing and quantifying humic acid content and quality, leading to inconsistencies in commercial formulations and difficulties in establishing clear structure-function relationships. Additionally, the mechanisms by which humic acid influences plant growth, nutrient uptake, and soil properties are not yet fully elucidated at the molecular level, particularly regarding its interactions with plant hormone signalling pathways, root architecture modification, and rhizosphere microbial communities, which limits the ability to optimize application strategies for specific crops and soil conditions.

Dose-dependent and context-specific responses present another major challenge, as the effectiveness of humic acid varies considerably depending on soil type, pH, organic matter content, climatic conditions, and crop species, often resulting in inconsistent or contradictory findings across field trials conducted in different agroecological zones. The interaction of humic acid with other soil amendments, fertilizers, and agrochemicals remains poorly understood, raising concerns about potential antagonistic or synergistic effects that could compromise nutrient use efficiency if not properly managed. From a practical standpoint, the cost-effectiveness of humic acid application at commercial scales, particularly for resource-limited farmers, remains a concern, as does the challenge of ensuring product authenticity and preventing adulteration in a market where quality control standards are not rigorously enforced globally.

Furthermore, most existing research is based on short-term greenhouse or pot studies, and there is a notable scarcity of long-term field experiments that can validate the sustained benefits of humic acid on soil health indicators, carbon sequestration, and crop productivity across multiple growing seasons. The lack of standardized application rates, timing, and methods (soil application versus foliar spray versus seed treatment) further complicates the development of universal best-practice guidelines. Finally, regulatory frameworks governing humic acid products differ widely across countries, creating challenges for quality assurance, labelling accuracy, and international trade, while also highlighting the need for more robust, multi-location, and multi-year research to bridge the gap between experimental findings and practical, scalable recommendations for farmers.

6. Future thrust

Future research on humic acid application in agriculture must prioritize several key directions to bridge existing knowledge gaps and translate scientific findings into practical, scalable solutions for farmers. There is an urgent need to develop standardized protocols for humic acid extraction, characterization, and quality assessment, employing advanced analytical techniques such as nuclear magnetic resonance (NMR), Fourier-transform infrared spectroscopy (FTIR), and high-resolution mass spectrometry to establish clear structure-activity relationships that can guide the selection of source materials for specific agricultural applications. Future studies should focus on elucidating the precise molecular mechanisms underlying humic acid's bio stimulant effects, particularly its interactions with plant hormone signalling pathways (auxin, cytokinin, and gibberellin crosstalk), ion transporter regulation, and epigenetic modifications that influence stress tolerance and nutrient acquisition, potentially through integrated multi-omics approaches combining transcriptomics, proteomics, and metabolomics.

Long-term, multi-location field trials spanning diverse agroecological zones and cropping systems are essential to validate the sustained impacts of humic acid on soil health parameters, including microbial diversity, carbon sequestration potential, and aggregate stability, moving beyond the current reliance on short-duration greenhouse studies. Research should also explore the synergistic potential of humic acid when combined with other sustainable agricultural inputs such as biofertilizers, plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and nanotechnology-based delivery systems, aiming to develop integrated nutrient management strategies that maximize resource use efficiency while minimizing chemical fertilizer dependency.

The development of site-specific and crop-specific application guidelines, informed by precision agriculture technologies and soil-test-based recommendations, represents another critical thrust area, as this would allow farmers to optimize dosage, timing, and application methods based on real-time soil and crop conditions. Additionally, there is significant scope for exploring humic acid's role in enhancing plant resilience to abiotic stresses such as drought, salinity, and heavy metal toxicity in the context of climate change, which could position it as a valuable tool for climate-smart agriculture.

Future work should also investigate the economic viability and cost-benefit analysis of humic acid products across different farming scales, particularly for smallholder farmers in developing regions, alongside efforts to develop low-cost, locally-sourced humic acid extraction technologies that could improve accessibility. Furthermore, establishing harmonized international regulatory standards and quality certification systems would help ensure product authenticity, prevent market adulteration, and facilitate global trade while building farmer confidence.

Finally, interdisciplinary collaboration between soil scientists, plant physiologists, agricultural economists, and policymakers will be crucial to translate laboratory and field research findings into evidence-based extension programs and policy frameworks that promote the sustainable and widespread adoption of humic acid technologies in modern agriculture, ultimately contributing to global food security and environmental sustainability goals

7. CONCLUSION

Humic acid stands out as a multifaceted and promising natural amendment capable of simultaneously addressing the interconnected challenges of crop productivity, nutrient use efficiency, and soil health degradation that threaten the sustainability of modern agricultural systems. The extensive body of research reviewed demonstrates that humic acid's diverse biochemical and physiological actions ranging from enhanced root proliferation and improved nutrient chelation to stimulated microbial activity and strengthened plant stress tolerance translate into tangible benefits across a wide range of crops and growing conditions, offering a viable pathway toward reducing dependency on synthetic fertilizers while maintaining or even improving yield outcomes.

Its capacity to improve soil physical structure, enhance cation exchange capacity, foster beneficial microbial communities, and sequester carbon further underscores its value not merely as a yield-enhancing input but as a long-term investment in soil ecosystem resilience and environmental sustainability. However, realizing the full potential of humic acid in mainstream agriculture requires overcoming the variability in product quality, filling critical gaps in mechanistic understanding, and generating robust long-term field evidence that can inform standardized, region-specific application practices.

As global agriculture confronts mounting pressures from climate change, soil degradation, and the need for more resource-efficient production systems, humic acid-based technologies offer a scientifically grounded and ecologically sound strategy that aligns with the broader goals of sustainable intensification. Continued interdisciplinary research, coupled with supportive regulatory frameworks and farmer-focused extension efforts, will be essential to fully harness humic acid's potential, ensuring that this valuable natural resource contributes meaningfully to global efforts toward achieving food security, economic viability for farmers, and long-term environmental stewardship in the decades ahead.

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Author contributions

Sadhana K contributed to the conceptualization and preparation of original draft. Maragatham S contributed to conceptualization and editing the original draft. Malathi P, Sellamuthu K M, Rajeswari R, Senthil A, Kavitha M, and Divya K Lekshmanan contributed to the review and editing of the manuscript. All authors reviewed and approved the final version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing interests.

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