PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.8487

eISSN 2348-1900

REVIEW ARTICLE

Application of fulvic acid in agriculture: An overview

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Received: 24 March 2025; Accepted: 09 May 2025; Available online: Version 1.0: 28 May 2025

Cite this article: Pavadharini P, Sakthivel N, Ramah K, Sivasakthivelan P, Senthil VP, Kabilan M, Vasumathi V. Application of fulvic acid in agriculture: An overview. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.8487

Abstract

Fulvic acids, an essential fraction of soil organic matter, have emerged as influential agents in enhancing soil fertility and boosting crop productivity. This review compiles and analyzes recent scientific literature to clarify the diverse roles fulvic acids play within soil ecosystems and their subsequent effects on plant growth and agricultural yield. The methodology involved a comprehensive review of 150 relevant articles, including 100 peer-reviewed studies from databases such as Web of Science, ResearchGate, PubMed and Google Scholar. Initially, the interactions between fulvic acids and various soil components are discussed, demonstrating their ability to improve soil structure, increase nutrient retention and enhance nutrient availability across a range of soil types. The review further evaluates the outcomes of fulvic acid application on crop growth in different agricultural systems under varying environmental conditions. In addition, the potential of fulvic acids to act synergistically with other soil amendments and fertilizers is explored, offering insights into integrated strategies for sustainable agricultural management. Collectively, the findings highlight fulvic acids as multifunctional agents that improve soil quality and contribute to increased crop resilience and sustainability in modern farming systems.

Keywords: crop performance; fulvic acid; mitigates stress; soil interaction

Introduction

Plants encounter a range of stresses during their life cycle, including both biotic and abiotic factors (1). These stresses significantly reduce crop yield by disrupting the plant's metabolism. Abiotic stresses arise from the combined effects of intensive human activities, rapid industrialization and the impacts of climate change. Abiotic stress includes drought, salinity, extreme temperatures and heavy metal toxicity, which disrupts water balance, nutrient uptake and metabolic processes, leading to reduced growth and yield. Whereas biotic stress refers to the negative impact on plants caused by living organisms, such as bacteria, viruses, fungi, parasites, insects and weeds. Due to the unpredictable nature of environmental stresses, innovations in agricultural inputs have been developed to minimize their negative impacts. In this context synthetic fertilizers, herbicides and pesticides are widely utilized (2). These inputs can improve crop management efficiency and yield; however, their excessive and improper use can cause environmental pollution, endangering various organisms, including humans. Studies estimate that only about 0.1 % of applied herbicides and pesticides effectively target the intended species, while the rest contaminate the environment (3). As humans occupy the top of the food chain, they are exposed to agrichemical compounds that have accumulated in lower trophic levels. These substances can interfere with enzyme activity, disrupt transcription and translation and hinder metabolism in the human body. Consequently, there is an increasing demand for alternative approaches to replace these conventional agri inputs (4).

Biostimulants have gained recognition as an innovative and environmentally sustainable approach for promoting plant growth and increasing crop productivity, even under challenging conditions. This progress is considered a significant scientific breakthrough in advancing sustainable food production for the future (5). It enhances crop resilience to environmental stresses such as drought, extreme temperatures and soil salinity. Unlike numerous artificial fertilizers and pesticides, biostimulants are predominantly obtained from natural origins and present a reduced risk of ecological contamination. They are less prone to causing issues such as nutrient runoff, which can lead to water pollution and algal overgrowth. By improving soil health, biostimulants can strengthen natural pest and disease resistance, possibly lowering the need for chemical pesticides (6). The main categories of plant biostimulants are mentioned in the Fig. 1 (7). Among various biostimulants, this review specifically highlights humic substances, focusing on fulvic acid.

Humic substances (HS) are naturally occurring elements of soil organic matter, originating from the breakdown of plant and animal remains and the action of microorganisms in the soil. They are also widely found in

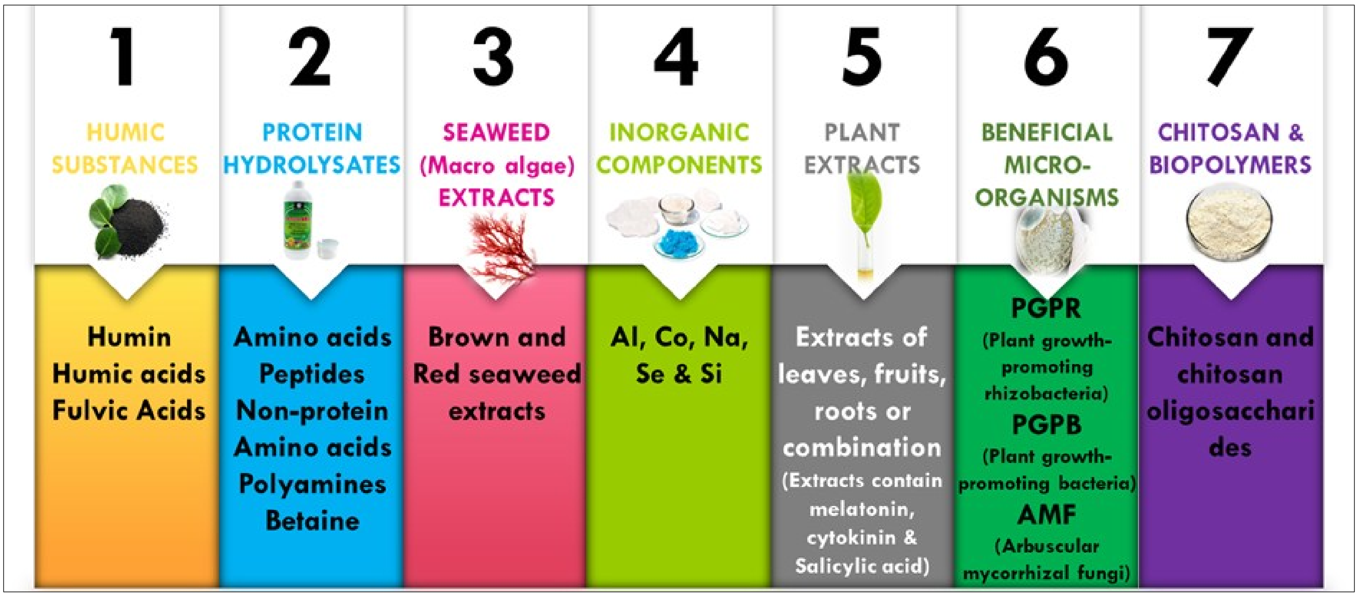

Fig. 1. Classification of biostimulants.

aquatic ecosystems. They interact with clay to form complexes in which hydrophilic compounds accumulate at the core of the aggregates, while hydrophobic compounds are located on the outer layer. Hence, water penetration into the aggregates is limited, enhancing soil aeration, root penetration, resistance to soil erosion and overall soil structure. This process ultimately increases the availability of nutrients for plants (8). The effectiveness of HS in agriculture is influenced by their origin, application dosage and environmental conditions (9). Fulvic acid (FA) is one of the humic substances and the others include humin and humic acids (HA). FA functions as a natural chelator of essential minerals, improving their bioavailability and facilitating nutrient absorption. The application of FA or HA significantly alleviated the effects of drought by preserving chlorophyll levels and supporting gas exchange, likely due to increased activity of antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT), along with higher proline levels (10). These beneficial effects contribute to improving plant growth and increasing grain yield. Additionally, it enhances the permeability of plant cell membranes, allowing micronutrients like zinc to enter plant tissues more efficiently, thereby improving nutrient uptake (11). FA increases nutrients and restructures the microbial community, potentially improving soil quality and biological control of diseases. FA improves the soil microbial community of nitrogen cycle and reduces the loss of nutrients. By highlighting the applications of FA, this review provides a brief overview of its application rates across various crops and its interactions within the soil, plant and microbial interface. It plays a vital role in sustainable crop production by improving soil structure, enhancing nutrient uptake and increasing microbial activity. Its use reduces the need for chemical fertilizers, promoting environmentally friendly and efficient farming practices. Additionally, it explores the mechanisms through which FA enhances stress tolerance, promotes plant growth and supports development, incorporating recent advances in the field.

Methodology

A structured literature review was conducted to explore the industrial applications of fulvic acid in agriculture with a focus on sustainability. Relevant articles were sourced from major scientific databases, including PubMed, Research gate, Web of Science and Google Scholar. The search covered publications from the past decade (approximately 2014-2025), using keywords such as "fulvic acid," "agriculture," "sustainability," "soil amendment" and "plant growth." An initial pool of approximately 150 articles was identified. After a thorough screening process based on titles, abstracts and full-text reviews, 100 articles were selected for detailed analysis. The main inclusion criterion was the article's relevance to sustainable agricultural practices, particularly studies highlighting fulvic acid's role in promoting soil health, improving nutrient efficiency, improving crop performance and mitigating stress. Non-English articles, non-peer-reviewed reports and studies not directly addressing sustainability aspects were excluded. Data extracted from the selected studies included the source of fulvic acid, crop types, observed agronomic benefits and reported contributions to sustainable farming. The information was synthesized qualitatively to provide an updated overview of fulvic acid's relevance in agriculture under the lens of sustainability.

Fulvic acid - structure and properties

FA is one of the most intriguing and valuable components of humic substances. Compared to other HS fractions, such as humic acids and humin, FA has a low molecular weight (~500-2000 Da) (12), higher solubility and greater stability across different pH levels (13). Its structure is richer in oxygen-containing compounds (12) and exhibits lower aromaticity (14). FA is composed of aromatic organic polymers, which are loosely assembled. It has an open carbon structure, a macro molecular mixture, consisting of aliphatic and aromatic compounds which is mentioned in the Fig. 2. It has the chemical formula $C_{14}H_{12}O_8$ and a molecular weight of 308.24 g/mol, reflecting its complex organic structure rich in oxygen-containing functional groups. FA has a strong adsorption capacity for positively charged substances, making it

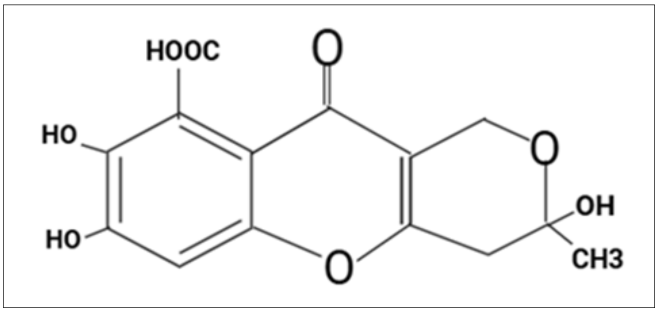

Fig. 2. Structure of FA.

essential in regulating the speciation, bioavailability, toxicity and mobility of metals (15). The absence of metal chelates, such as Zn, Cu and Fe, reduces the availability of these elements, leading to its deficiencies in plants and inhibiting root growth (16). The chelating effect of FA can reduce the positive charge of cations, enhancing the migration of micronutrients to the plant (17). The carboxyl and phenolic groups of HS play a key role in metal ion complexation. As an effective tool for metal remediation, FA has a greater abundance of oxygen-containing functional groups, including carboxyl, phenolic hydroxyl, alcoholic hydroxyl, amino, quinone, sulfhydryl and methoxy groups, compared to humin and HA. This enables FA to bind metal ions more effectively than other HS components, significantly influencing the migration, transformation, toxicity and bioavailability of metals in sediments (18). FA can function as both a reducing and oxidizing agent, playing a role in the redox reactions of metal contaminants and contributing significantly to ecological restoration. Commercially available products like FULVAGRA® Liquid 25 and AgroLiquid Fulvic highlight the agricultural potential of fulvic acids. FULVAGRA® Liquid 25 is a highly active liquid formulation derived from aquatic sources of fulvic acids, suitable for foliar sprays, soil treatments and hydroponic cultivation. It enhances nutrient uptake and supports overall plant vitality. Similarly, AgroLiquid Fulvic is a water-soluble fulvic acid fertilizer that restores humic substances in the soil, improves nutrient availability and promotes vigorous plant growth.

Methods of extraction of fulvic acid

Fulvic acid (FA) can be extracted from various natural sources using different extraction procedures, such as alkaline extraction with sodium hydroxide and oxidation using hydrogen peroxide. Other methods include microwave-assisted oxidative extraction, ionic liquid-based extraction and alkaline extraction using magnetized water, as briefly summarized in Table 1. The method developed by the International Humic Substances Society (IHSS) is widely recognized as the standard approach for extracting humic substances from soils. This procedure is briefly illustrated in Fig. 3.

Table 1. Sources and extraction methods of FA

Sources	Method of extraction	References
Corn straw	Alkaline extraction using sodium hydroxide (NaOH) followed by acid precipitation.	(19)
Lignite	Oxidation using hydrogen peroxide (H_2O_2) in combination with NaOH or potassium hydroxide (KOH), with the addition of silicone defoamer to reduce foam formation	(20)
Soil samples	Experimental and DFT Studies on the Efficient Extraction and Formation Mechanism of Fulvic Acid from Lignite	IHSS
Humus materials e.g., oxidized lignite	Mixing ground humus material with water to solubilize fulvic acid molecules, followed by microbial oxidation and ultrafiltration to separate fulvic acid from humin and humic acid.	Patent No: EP1797190A1
Low rank-lignite	Microwave-assisted oxidative extraction	(21)
Wood biomass	Ionic liquid-based extraction	(22)
Coffee, manure and other plant residues	Alkaline extraction with magnetized water	(23)
Oil palm (empty fruit bunches)	Microwave-assisted extraction using hydrogen peroxide	(24)

Interaction of fulvic acid in soil properties

Effect on physico-chemical properties

FA directly influences soil physicochemical properties, enhances cation exchange capacity (CEC) and supports soil structure and its stability. Due to the presence of COOH, OH groups and phenolic groups, it helps in improving soil structure and fertility. It strongly affects the release of macronutrients N, P and K (25). It increases the soil organic carbon, available nitrogen and available phosphorous but decreases the available potassium. The rise in soil organic carbon was due to FA, which is made up of organic particles that promote the mineralization of organic matter within the soil. In clay soils, it helps in loosening the compacted soils, facilitating better water infiltration and promoting root growth and development (26).

Soil pH and electrical conductivity (EC) are key factors in soil health. They regulate soil acidity, maintain stability and influence the release of carbon dioxide (27). FA increases the EC and decreases the pH of the soil. The increase in electrical conductivity is due to the dominance of ion dissolution over biological assimilation or ion pair formation. HS have established a buffer system due to the presence of functional groups that stabilize the soil pH. This buffering capacity is a key characteristic of FA molecules, which is a component of HS. Humic substances like humic acid and fulvic acid improve various soil properties, including water-holding capacity, by promoting aggregation and enhancing soil aeration (28). This creates favourable conditions for microbial activity, which accelerates the mineralization of organic matter and increases the bioavailability of both micro and macronutrients for plant uptake (29).

Soil enzymes, produced by microorganisms, plant roots and soil organisms, act as biological catalysts that support nutrient cycling, organic matter breakdown and overall soil health. FA enhances soil enzyme activity because it has a lower carbon-to-oxygen (C:O) ratio than HA, making it more soluble in water and more accessible to microorganisms (30). It has more reactive sites, including carboxyl, phenol and hydroxyl groups, which bind with heavy metals and extract them from soil solutions, thereby lowering their toxicity (31).

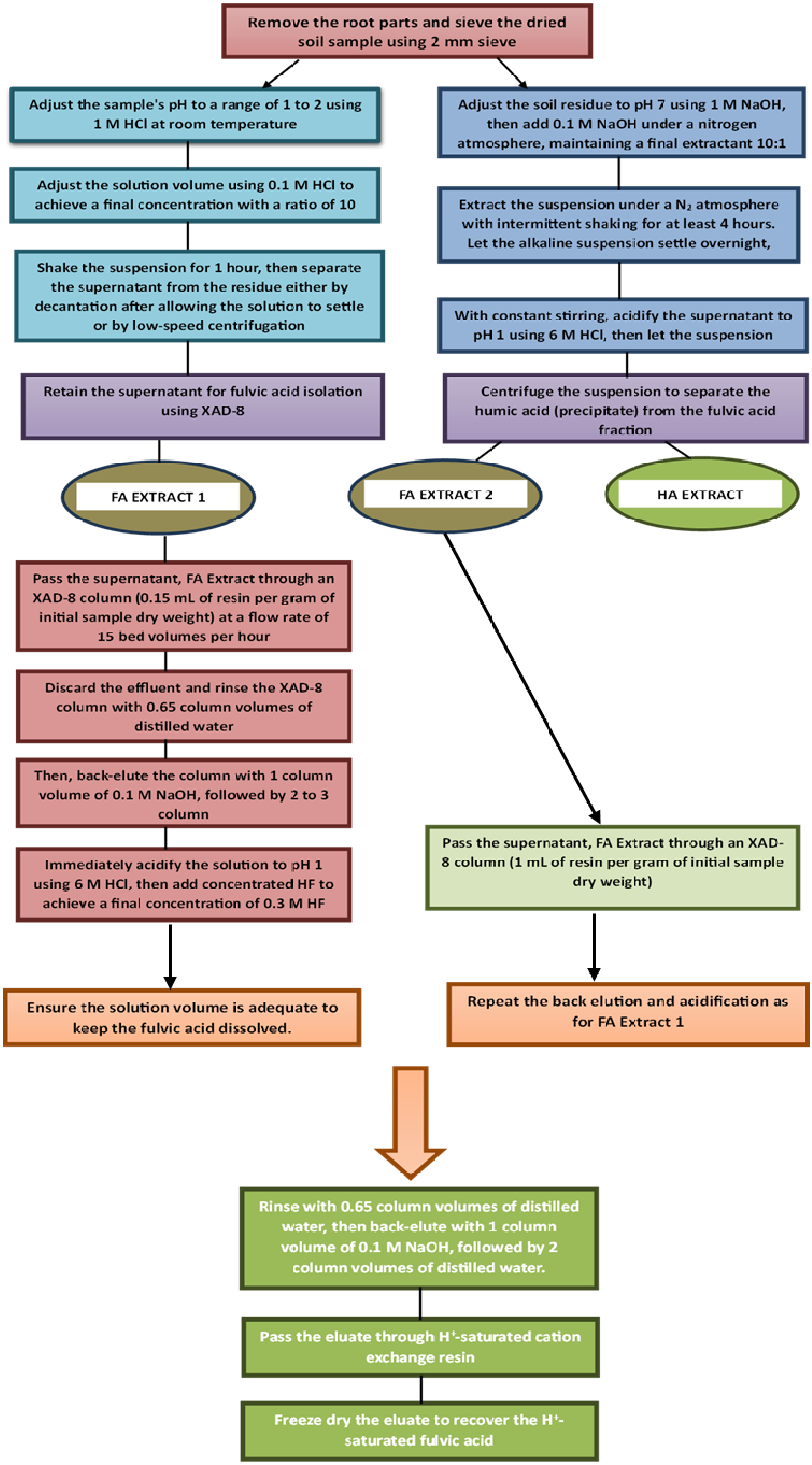

Fig. 3. Procedure for extraction of FA from soil samples given by IHSS.

Effect on microbial activity

The organic matter and nutrients present in the soil is essential for the growth and multiplication of microorganisms. HA and FA are key components of soil organic matter that impact plant growth and support microbial activity (32). FA is primarily recognized for its antioxidant properties (33), while HA demonstrates various biological activities beneficial to plant cultivation, pharmacology and ecology. The antioxidant property of FA plays a crucial role in microbial activity in soil by influencing microbial metabolism, protecting cells from oxidative stress and modulating biochemical interactions in the soil environment. FA improves the soil microbial community by regulating the nitrogen cycle, reduces the loss of nutrients which act as a carbon source for the growth of microorganisms. Since it contains many active ions, which promotes the growth and nitrogen fixation ability provides a carbon source for the growth of microorganisms (34). It enhances the growth of the bacterial community, primarily *Azotobacter*, by stimulating their respiration and nitrogen fixation (35).

It enhances nitrogen fixation and promotes key microorganisms belongs to families like Azospirillaceae, Methanosarcinaceae and Bathyarchaeota (36). FA also promotes symbiosis between legumes and rhizobia and alters root exudate metabolite composition and increases gene expression related to isoflavonoid biosynthesis. It induces changes in the rhizosphere microbial community, coupled with an increase in the relative abundance of rhizobia (37).

Effect on nutrient availability and uptake

Fertilizer efficiency depends on crop absorption and soil nutrient supply. Urea (46 % N) is the most nitrogen-rich inorganic fertilizer, accounting for 40 % of total nitrogen fertilizer use. At 20-25°C, soil microorganisms and plant-root urease hydrolyze urea into ammonium bicarbonate within 5-7 days (38). Plants absorb $NH4^{+}$ for growth, while unabsorbed $NH4^{+}$ binds to soil colloids or oxidizes to NO^{2-} and then NO^{3-} by nitrifying bacteria (39). Nitrate is highly mobile, leading to runoff into surface waters or leaching into groundwater, causing eutrophication. Combining inorganic fertilizers with organic amendments is a key strategy for sustaining agricultural systems (40). Applying urea with FA solution improves soil nutrient availability, increases endogenous hormone levels, activates nitrogen metabolism enzymes, enhances photosynthetic carbon assimilation and ultimately increases crop yield and nitrogen use efficiency (NUE) (41). The phenolic, hydroxyl and quinone groups in fulvic acid interact with the sulfhydryl groups in urease, inhibiting urease activity and reducing ammonia volatilization from urea. The carboxyl and phenolic hydroxyl groups engage with the amide groups in urea through coordination complexation, ion exchange or hydrogen bonding, forming stable fulvic acid-urea complexes that slow down urea decomposition. They also react with $NH4^{+}$, forming stable fulvic acid-ammonium salts (42), which enhances $NH4^{+}$ availability to meet plant nitrogen demand during critical growth stages (43).

FA, a low-molecular weight component of humic substances, significantly influences the availability and mobility of P and K in soil, enhancing nutrient uptake by plants. In soil, phosphorous often becomes immobilized and unavailable to plants due to reactions with calcium (Ca) in alkaline soils or iron (Fe) and aluminum (Al) in acidic soils. FA can decrease P adsorption in soils by interacting with soil components. A study found that FA reduced P adsorption in clay fractions of different soils, with the effect varying based on the sequence of FA and P application. FA applications have been shown to increase P availability. Research demonstrated that FA-treated soils exhibited higher phosphorus activation coefficients, indicating improved P desorption and availability. FA enhances soil microbial activity, leading to increased production of organic acids and enzymes that mobilize P. A study observed that FA application increased acidic phosphatase activity and dissolved organic carbon content, contributing to higher soil available phosphorus. K exists in three forms: soluble (available), exchangeable and fixed (trapped in clay layers) which cause a significant portion of K gets fixed in clay minerals, making it unavailable to plants. FA contains functional groups capable of absorbing and storing potassium ions, reducing leaching losses and increasing soil exchangeable potassium (44).

HA application increases the accumulation of minerals like Ca, Fe, Mg and Zn in soil-grown garlic (45). FA binds with Fe and other micronutrients, facilitating their transport across membranes and improving mineral accumulation in plants (46). According to (47), FA influences nutrient dynamics by regulating enzymes and genes involved in primary metabolism, thereby impacting the transformation and accumulation of metabolic substances (48). Application FA in combination with other nutrient sources has more significance which is given in the Table 2.

Impact of fulvic acid on crop growth and enhancement

Seed germination

FA at moderate concentrations (80-160 mg L^{-1}) increases the germination rate and vigour index of tomato seeds (48) and cucumber seeds (53). Soluble humates increase the germination rate by 31.6 % which is extracted from vermicomposted cattle manure (54). The enhancement of seed germination may be due to auxin-like compounds in humic products, which boost amylase activity and stimulate seed respiration (55). Seed dressing with FA reliably increases the germination percentage and decreases the mean germination time in spring wheat and spring barley (56). FA at a concentration of 0.5 % significantly promoted seed germination, coleoptile and radicle length and increased the activity of α-amylase and (α+β) amylase (57). Seed priming and foliar spray on pea plants (*Pisum sativum* L.) enhances seed germination, plant growth and productivity, with seed priming showing a more pronounced effect (58).

Plant growth

FA application promoted the vegetative stage and dry matter by the development of shoots, roots, leaf area and chlorophyll accumulation. Enhanced root growth improves nutrient uptake and utilization from the soil, leading to greater dry matter accumulation. It influences plant hormone signalling pathways and increases intracellular ATP and glucose-6-phosphate levels, promoting growth in cell cultures. It enhances the uptake of N and Mg, essential for chlorophyll structure, delays senescence and promotes chlorophyll accumulation, resulting in a higher photosynthesis rate (59).

Table 2. Synergistic effect of fulvic acid with other fertilizer

	Combinations	Significance	References
FA	Nitrogen fertilizers	Enhances the release and availability of phosphorus in salt-affected soils	(49)
	Controlled release urea (CRU)	Increases nitrate reductase, glutamate dehydrogenase and auxin levels in maize roots and leaves, enhancing the C:N metabolic process.	(34)
	Bacillus paralicheniformis	Reduce bacterial wilt disease, improve soil fertility and enhance plant resistance to bacterial wilt disease	(50)
	Biofertilizers	Improve soil phosphorus availability, plant phosphorus uptake and grain yield	(51)
	Chelated with potassium	Improves soil health, promotes plant growth and enhances plant disease resistance	(52)

It increases the levels of essential amino acids like lysine, phenylalanine and tryptophan, as well as the non-essential amino acid arginine, which serve as key precursors for secondary metabolites in plants. Humic substances activate key enzymes that initiate phenolic biosynthesis by converting phenylalanine to trans-cinnamic acid and tyrosine to p-coumaric acid (60), results in increased phenolic accumulation in tomato leaves (54). FA helps in promoting various growth parameters as listed in Table 3.

Root development

FA enhances auxin and gibberellin, which promotes the elongation of root cells, coleoptiles and hypocotyls (47). Auxin is crucial for lateral root initiation, promoting root branching by triggering the formation of lateral root primordia. It also influences root elongation by stimulating cell division and expansion in the root meristem. Gibberellins complement auxin by promoting cell elongation in both primary and lateral roots, ensuring optimal root length. They also interact with auxins to regulate meristem size and maintain overall root growth balance. Fulvic acid enhances root length in wheat (57) and number and length of lateral roots of tomato plants (71). Similarly, humic extracts promote the growth of radicles and seminal lateral roots in maize seeds (72). HS enhances the activity of genes and enzymes responsible for nutrient transport from roots to shoots (73). The increase in root growth increases the nutrient uptake of vegetable plants. Thus, enhancement in plant root growth improves the production and quality of the crops (48). Also, it improves the length and biomass of rice seedlings, including both shoot and root. Humic substances enhance plant growth and physiology by increasing root length and density, which expands the absorptive surface area and improves nutrient uptake (74) and also in various crops as listed in Table 3.

Yield and quality improvement in various crops

HS, enhance plant strength by improving nutrient absorption through the roots. This results in an increase in the tillers and spike of wheat. They achieve this by chelating essential minerals, making them more available to plants and stimulating root growth, leading to a more extensive root system (75). It enhances maize growth and yield by improving nitrogen uptake, promoting photosynthesis, increasing carbon/nitrogen metabolic processes and enhancing enzyme activities (76). FA at a moderate dose can improve rice growth and phosphorus utilization, making it an effective component of a sustainable agricultural production fertilizer (77). It enhances pea productivity and improves its nutritional quality through the seed priming technique (58). Yield and quality of tomatoes are improved by facilitating root growth and nutrient uptake (48). Enhancing soil water-stable macroaggregates, optimizing moisture distribution and promoting desalinization in saline soils contribute to improved cotton yield and growth (78). It improves the quality and yield of apples by reducing manganese and copper content in soil and promoting plant growth (79). It improves broccoli yield by increasing plant height, flower disk weight and total leaf area (80). It also enhances the yield and quality of various crops, as shown in Table 3.

Effective amendment in restoring poor soils

FA application has improved soil physicochemical properties in saline environments. It enhances soil water-stable macroaggregates, moisture distribution and desalinization, leading to a significant reduction in soil salinity and pH levels (78). It also increases soil organic matter content and improves soil permeability, which facilitates better water and salt transport (78). The application of HA increases plant growth, photosynthetic processes, antioxidant enzyme activity under salinity stress conditions (84). When FA is applied in acid soils, it has been shown to increase soil pH, which helps in reducing the concentration of exchangeable aluminum, which is a common issue in acidic soils. This reduction in aluminum concentration significantly increases the availability of phosphorus, an essential nutrient for plant growth. The movement of phosphorus in the soil is also enhanced, improving its accessibility to plants. Hence, it improves soil fertility and structure, which are crucial for healthy plant growth (85). Interacting with soil minerals and organic matter, helps to neutralize excessive acidity, thereby creating a more favourable environment for plant roots. It enhances nutrient uptake by chelating vital minerals, making them more soluble and accessible to plants. This chelation process is particularly beneficial in acidic conditions where nutrient availability is compromised. Fulvic acid can lower soil pH and replace sodium ions, thereby improving soil structure and reducing sodicity (86). It can improve phosphorus availability by interacting with nitrogen fertilizers, which enhances phosphorus recovery in salt-affected soils (49).

Fulvic acid role in abiotic and biotic stress tolerance

Abiotic stress

Drought stress in plants causes wilting, reduced growth and lower productivity. Drought stress disrupts the photosynthetic mechanism, stomatal regulation, water transport mechanism, nutrient uptake and transport, enzymatic and metabolic functions and reproductive mechanisms. FA mitigates drought stress by minimizing membrane lipid peroxidation and regulating the antioxidant system, phenylpropanoid biosynthesis and glutathione metabolism pathways. It prevented the accumulation of malondialdehyde (MDA),

Table 3. Impact of fulvic acid on plant growth and yield parameters

	FA rate	Combination	Crop	Significance	References
FA	0.5mM	FA-releasing chitosan nanoparticles (Ch-FANPs)	Rice	Increases shoot length Improves photosynthetic efficiency Increases root length	(61)
	100 µM	Chitosan-FA nanoparticles (Chitosan combined with FA)	Maize	Increases shoot length Increases root length, root fresh and dry weight	(62)
	3000 ppm	NAA	"Taimour" Mango	Increases the levels of N, Pand K content in leaves. Enhances leaf surface area and total chlorophyll content, Increases the number of fruits per tree, increases total soluble solids (TSS) (%), acidity (%), total sugars (%), reducing sugars (%) and Vitamin C	(63)
	4 g/L	Herd manure Brassinolide	Pomegranate	Increases shoot length and leaf area. Increases leaf N and P content Improves absorption capacity of roots	(64)
	6 g/L	Humic acid Proline	Sunflower	Increases the permeability of cell membrane and photosynthetic efficiency. Increases the number of leaves stem diameter. Increases leaf chlorophyll content and plant dry weight, increases 1000 seed weight, increases percentage of oil in seeds and percentage of protein in seeds	(65)
	100 mg/L	Humic acid Amino acid	Olive	Increases chlorophyll a and total chlorophyll content in leaves	(66)
	4 g/L	RDF Mango waste biochar Cobalt	Chilli	Increases plant height and number of primary branches. Increases total chlorophyll content	(67)
	3 g/L	Fe-fulvic acid	Pepper	Increases the biomass of the stem and root	(68)
	40 ppm	Vermicompost Amino acids	Iceberg lettuce	Increases plant height, leaf area and number of leaves Increases root weight	(69)
	4 L/ha	Seaweed extract *(Ascophyllum nodosum)*	Sicilian oregano	Increases plant height and chlorophyll content	(70)
	2.5 kg/ha	Chelated zinc (Zn-EDTA)	Maize	Increases plant height, stem girth and number of leaves, increases chlorophyll content, increases the number of cobs per plant, length and weight of cob , improves seed index, grain yield, stover yield and harvest index	(81)
	2500 ml/ha	Macronutrients Micronutrients Humic acid	Triticale	Increases plant height and number of spikes, Increases the number of grains per spike and its weight	(82)
	5 L/time/tree	Humic acid	Lemon	Increases the weight of the lemon fruit, increases the yield of lemon juice and edible rate of the fruit, increases Vitamin C, total acid and total sugar content of the fruit	(83)

hydrogen peroxide (H_2O_2) and dehydroascorbic acid (DHA), thereby minimizing oxidative damage (87). Also mitigates nitrate stress by increasing oxidation resistance, photosynthetic capacity and redundant calcium nitrate (88).

Cadmium (Cd) is a significant pollutant due to its high toxicity and high solubility in water. It can disrupt mineral absorption by affecting the availability of minerals in the soil or by reducing soil microbial populations. Additionally, cadmium negatively impacts stomatal conductivity, transpiration and photosynthetic efficiency. Common symptoms of cadmium toxicity in plants include chlorosis, leaf curling and stunted growth. Furthermore, Cd inhibits nitrate reductase activity, leading to decreased nitrate uptake and reduced transport from roots to shoots (89). Foliar application of FA at 20 % concentration reduces metal uptake and its translocation to various parts of the plants (90). It mitigates heavy metal toxicity by increasing reactive oxygen species scavenging capacity, inhibiting the heavy metal uptake and the transport of elemental nutrients to the shoots, which protects photosynthetic apparatus and promotes plant growth (91). When temperatures rise above a plant's tolerance level, it can lead to reduced photosynthesis, protein denaturation, increased respiration and water loss. Fulvic acid at the concentrations of 3.75 mg L^{-1} and 2.50 mg L^{-1} causes thermotolerance in plants and substantially increase chlorophyll content and growth-related parameters especially at booting and grain-filling stages. It improves vegetative growth, mineral content and photosynthetic pigments of leaves, yield and quality (92). Heat stress is reduced by inducing the expression of antioxidant enzymes and cytochrome c oxidases and regulating stress response through rubisco and cytochrome c oxidase expression (93). FA mitigates abiotic stresses in various crops as listed in the Table 4.

Biotic stress

Fulvic acid has been studied for its potential to reduce plant diseases. It is used as a biostimulator and applied to restore soil health and control bacterial wilt disease. Fulvic acid when fermented with *B. paralicheniformis,* effectively suppresses bacterial wilt disease, improves soil quality, enriches beneficial bacteria and increases microbial diversity. Some key microorganisms in the treated soils exhibit antimicrobial properties and plant growth-promoting traits. This serves as a valuable tool for restoring soil health, enhancing microbiota and controlling bacterial wilt disease (50).

Table 4. Role of fulvic acid in mitigating stress

	FA rate	Crop	Significance	References
	0.5mM	Rice	Increase ascorbate peroxidase (APX) activity	(61)
	4.75 L/ha	Barley	Increase proline content and withstand salinity stress	(84)
	100 µM	Maize	Decreases the accumulation of H_2O_2, activates ascorbate peroxidase	(62)
	0.15 %	Spinch	Scavenges reactive oxygen species reduces intracellular oxidative damage by the accumulation of aspartic acid and arginine, increases accumulation of primary metabolites, improves Fe, Zn and Na, Increases organic acid content	(94)
	20 %	Canola	Reduces Cr, Cd and Pb levels in shoots, enhances the activity of antioxidant enzymes	(90)
	3 g/L	Pepper	Reduces Cd and Ba content in leaf tissues Increases Vitamin C and phenolic compounds and enhances the activity of POD, SOD and CAT enzymes	(68)
FA	1.5 g/L	Pistachio	Increases total phenol and flavonoid content, increases antioxidant properties and increases the activity of catalase, super oxide dismutase, ascorbate peroxidase and peroxidase enzymes	(95)
	4 g/L	Pomegranate	Increases shoot length and leaf area, increases leaf N and P content and improves absorption capacity of roots	(64)
	4 L/ha	*Sicilian oregano*	Increases the antioxidant, antimicrobial, anti-inflammatory and aromatic properties	(70)
	40 ppm	Iceberg lettuce	Increases total phenols and flavonoid content Decreases nitrate accumulation in leaves	(69)
	100 mg/L	Olive	Increases the activity of catalase and peroxidase	(66)
	4 g/L	Chilli	Increases plant height and number of primary branches. Increases fruit length and girth. Increases N and K content, increases total chlorophyll content	(67)
	10 g/L	Shanghai Bok Choy	Improves antioxidant enzyme activities such as catalase and super oxide dismutase	(96)
	0.5 %	Alfalfa	Reduces the mobility and bioavailability of molybdenum (Mo)	(97)

Gray mold in grapes, caused by *Botrytis cinerea*, results in fuzzy grey fungal growth, berry rot and yield loss, particularly in humid conditions. Its occurrence can be reduced by regulating polyphenol metabolism and increasing the accumulation of phenolic compounds, flavonoids and key enzymes such as phenylalanine ammonia-lyase (PAL), cinnamate-4-hydroxylase (C4H) and 4-coumarate-CoA ligase (4CL)(98). It increases the relative abundances of beneficial bacteria such as *Pseudomonas*, *Flavobacterium*, *Duganella*and *Massilia*, while decreasing harmful fungi like *Fusarium* and *Sistotrema* (99). Also, promotes legume–rhizobium symbiosis by enhancing the synthesis and secretion of endogenous flavonoids in soybeans. This leads to an increase in rhizobia accumulation in the rhizosphere, benefiting nitrogen fixation and plant growth (37). An investigation into Asian seabass juveniles showed that dietary fulvic acid supplementation enhanced growth, stress tolerance and disease resistance against *Vibrio harveyi*. Fish fed with fulvic acid exhibited improved immune responses and survival rates (100).

Future prospects of fulvic acids in agriculture

Fulvic acid holds great promise in sustainable and precision agriculture by enhancing nutrient uptake, improving fertilizer efficiency and reducing nutrient wastage. As a natural chelating agent, it boosts the solubility and absorption of essential minerals while promoting beneficial microbial activity and detoxifying soil contaminants like heavy metals. Beyond soil health, fulvic acid enhances plant growth, increases chlorophyll production and strengthens resilience against abiotic and biotic stresses. The future of fulvic acid in agriculture lies in its integration with precision farming technologies, such as smart irrigation and controlled nutrient delivery systems. There is growing interest in formulating advanced biofertilizers and biostimulants using fulvic acid, often in combination with microbial inoculants or other organic compounds. Research is also focusing on standardizing extraction methods and improving product consistency for large-scale applications. Moreover, expanding its use beyond agriculture into bioremediation, animal nutrition and environmental management could further enhance its industrial relevance. The development of eco-friendly, low-cost extraction technologies will be key to ensuring sustainable and scalable production of fulvic acid in the future.

Conclusion

Fulvic acid plays a vital role in soil health and plant growth by improving soil structure, aeration and water retention. It enhances oxygen flow to roots, promoting metabolic functions and reducing runoff, ensuring efficient water and nutrient conservation. Biologically, fulvic acid fosters microbial activity, accelerating organic matter decomposition and nutrient release, sustaining long-term soil fertility. Acting as a biostimulant, it activates hormonal pathways that enhance root development, crop vigour and biomass, leading to higher yields. Additionally, fulvic acid boosts photosynthesis by increasing nutrient absorption, particularly magnesium and iron for chlorophyll synthesis. Its water retention properties reduce wastage and irrigation needs, making agriculture more sustainable. By improving both soil and plant health, fulvic acid supports eco-friendly farming practices and maintain sustainability. Fulvic acid has demonstrated significant potential in various industrial applications, particularly in agriculture, environmental remediation, cosmetics and pharmaceuticals. Its proven benefits include enhanced nutrient absorption, improved soil health, metal detoxification and antioxidant properties, which have already led to its integration into fertilizers, soil conditioners, skincare formulations and health supplements. Future research should focus on expanding its applications in sustainable agriculture, green chemistry and biomedicine, positioning fulvic acid as a key natural resource for supporting eco-friendly innovation and enhancing human health. Greater regulatory clarity and industrial partnerships will also be critical to fully unlocking its commercial potential on a global scale.

Acknowledgements

We would like to express our sincere gratitude to Tamil Nadu Agricultural University for their support during the preparation of this review article.

Authors' contributions

PP prepared manuscript. SN and RK helped during collection of articles. SP[1] and SP[2] participated in the sequence alignment. KV drafted the manuscript and quoted the references. All authors read and approved the final manuscript. (SP[1]- Sivasakthivelan P and SP[2]- Senthilvalavan P).

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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