Plant Archives Vol. 26, No. 1, 2026 pp. 143-156 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.1.019

ROLE OF HUMIC ACID IN VEGETABLE CROP PERFORMANCE: A COMPREHENSIVE REVIEW

Swagat Ranjan Behera[1], Pragti Negi[2], B. R. Vasavi Devi[1], Uma Pant[1], Anjana Suresh[1], Rashi Chauhan[3], Diksha Joshi[4] and Riya Pandey[5]*

[1]Department of Vegetable Science, College of Agriculture, G.B. Pant University of Agriculture and Technology,
Pantnagar, Uttarakhand-263145, India
[2]Department of Vegetable Science, College of Horticulture, V.C.S.G. Uttarakhand University of Horticulture and Forestry,
Bharsar, Uttarakhand-246130, India
[3]Department of Agronomy, College of Agriculture, G.B. Pant University of Agriculture and Technology,
Pantnagar, Uttarakhand-263145, India
[4]Department of Soil Science, College of Agriculture, G.B. Pant University of Agriculture and Technology,
Pantnagar, Uttarakhand-263145, India
[5]Department of Agriculture, Invertis University, Bareilly, Uttar Pradesh-243123, India
*Corresponding author E-mail:pandeyriya510@gmail.com

(Date of Receiving-06-11-2025; Date of Revision-10-12-2025; Date of Acceptance-22-01-2026)

ABSTRACT

Humic acid (HA), a key fraction of soil organic matter, has garnered significant attention for its multifaceted role in improving crop productivity, especially under the dual challenges of nutrient depletion and abiotic stress in cropping systems. Although numerous studies have examined humic acid, a comprehensive overview of its benefits in vegetable production is lacking. This review synthesises recent advances in the structural, physiological and agronomic impacts of HA on vegetable crops, emphasising its function as a plant biostimulant. We aim to offer insights into how the complex molecular structure of HA improves soil aggregation and nutrient availability, culminating in enhanced growth, yield and quality of vegetable crops. Furthermore, HA improves plant resilience to various abiotic stressors by regulating ion accumulation and stimulating antioxidant enzymes. However, the responses vary with HA source, dose, application method, soil type and crop species, highlighting the need for crop-specific HA formulations and optimised application methods. Ultimately, this study seeks to integrate HA into nutrient management regimes to significantly reduce synthetic fertiliser input, paving the way for more resilient, nutritious and sustainable vegetable systems.

***Key words*: Abiotic stress, Crop performance, Humic acid, Plant biostimulant, Vegetables.**

Introduction

Humic acid (HA) is a major component of soil organic matter (SOM) and has long been recognised as an important natural biostimulant in agriculture. It is formed by the humification of plant and microbial residues (corresponding to 80% of SOM) (Amador *et al.*, 2018), resulting in complex, high-molecular-weight organic molecules enriched in aromatic rings and long aliphatic chains. These molecules contain numerous oxygen-containing functional groups (e.g., carboxyl, phenolic, hydroxyl and carbonyl), which give HA a high cation-exchange capacity (CEC) and the ability to chelate micronutrients and other ions. Consequently, HA improves soil properties and plant nutrition (de Aguiar *et al.*, 2022). For example, the addition of HA can increase soil aggregate stability (Chen *et al.*, 2017), water-holding capacity (WHC) (Billingham, 2020; Yang *et al.*, 2021), pH buffering (Ampong *et al.*, 2022) and microbial activity (Sible *et al.*, 2021), all of which support root growth and nutrient availability. In essence, HA acts as a multifunctional soil amendment that enhances crop productivity and sustainability.

In recent years, there has been a growing interest in the role of HA in enhancing crop performance under suboptimal conditions. Numerous studies have shown that HA applications can enhance plant growth, yield and nutrient use efficiency, especially when plants are under stress. For instance, HA treatments often increase root mass and length, stimulate photosynthesis and raise levels of growth-promoting hormones (e.g., auxins and cytokinins) (de Castro *et al.*, 2021; Laskosky *et al.*, 2020; Nardi *et al.*, 2021). These positive effects on basic physiology help plants grow more vigorously and utilise nutrients more effectively in both optimal and stressful environments. Simultaneously, the functional groups of HA also behave as natural antioxidants that scavenge reactive oxygen species (ROS), protecting plants from oxidative damage under stress (de Castro *et al.*, 2021; García *et al.*, 2016).

Vegetable crops, including leafy greens (lettuce, spinach), bulb/root/tuber crops (onion, carrot, potato) and fruiting vegetables (tomato, pepper, cucumber), are particularly important for human nutrition and market value. However, many vegetables have inherently low nutrient-use efficiency and are sensitive to abiotic stress (Tei *et al.*, 2020). This often leads to heavy fertilisation and water inputs, which can harm soil health and reduce crop quality (Zandonadi *et al.*, 2014). As a result, sustainable inputs such as HA have been actively explored in vegetable production.

Given these broad benefits, a clear understanding of the relationship between humic acid structure and function in plants, especially under stress, is needed. Therefore, this review focuses on the structure and properties of humic acid and its functions in plants, with an emphasis on vegetable crop performance. Throughout, we draw on recent (2018-2025) studies to provide an up-to-date scientific perspective.

Structure and properties of humic acid

Humic acid (HA) is not a single compound but a complex mixture of organic molecules derived from the decomposition of plant, microbial and animal matter. Humic substances (HS) are divided into three fractions based on solubility: humic acid (insoluble at acidic pH but soluble in alkaline media), fulvic acid (soluble in both acidic and alkaline media), and humin (insoluble in both) (de Melo *et al.*, 2016; Stevenson, 1994). In practice, HA is extracted as the alkali-soluble, acid-precipitating fraction of the SOM. It typically makes up 60-70% of soil humus carbon.

The molecular structure of humic acid is highly heterogeneous and polydisperse. It consists of large, irregular macromolecules and supramolecular assemblies held together by weak bonds (e.g. hydrogen bonds and hydrophobic interactions). The backbone of HA is largely aromatic (rings derived from lignin and tannins) and aliphatic (alkane-like chains), with abundant functional groups attached (Fischer, 2017). Characteristic functional groups include carboxyl (–COOH), phenolic hydroxyl (Ar–OH), alcoholic hydroxyl (–OH), carbonyl (–C=O), quinone and a smaller portion of nitrogen-containing moieties, of which –COOH and –OH groups are the most predominant (Nardi *et al.*, 2021). These groups are responsible for HA reactivity; for example, carboxyl and phenolic moieties dissociate to give HA a high CEC, and they readily bind metal cations, organic molecules and protons (H^+) (Ma *et al.*, 2024). The ability of HA to form stable complexes with metal ions (through chelation) and with organic compounds is a key property.

Chemically, HA contains approximately 50-70% carbon, oxygen and hydrogen, and smaller amounts of nitrogen and sulphur (Sible *et al.*, 2021). These compositions reflect its plant and soil origins. The relative proportions of aromatic and aliphatic content can vary with the source; for example, HA from well-humified peat may have a more aromatic character, whereas HA from compost may have more aliphatic and labile structures (Hamad and Tantawy, 2018). The average molecular weight of HA fractions also varies (from a few hundred to several thousand Daltons), but generally, high-MW HA has fewer free functional groups than the low-MW portion (de Melo *et al.*, 2016). Importantly, structure of HA can be altered by environmental interactions; for example, organic acids exuded by roots or soil microbes can intercalate into HA structures, changing their form and solubility (Nardi *et al.*, 2017).

Because of its amphiphilic nature (Mirza *et al.*, 2011), HA also influences soil physical properties. The hydrophilic (polar) regions, rich in –COOH and –OH groups, can hold water and bind nutrients, whereas hydrophobic (non-polar) regions tend to associate into aggregates (Billingham, 2020). In the soil, this leads to improved aggregate stability and increased water-holding capacity. In summary, HA is a biologically derived organic macromolecule with a complex mixture of aromatic rings, aliphatic chains and oxygenated functional groups. This unique structure underlies its multifunctional behaviour in soil and plants (Ma *et al.*, 2024).

Functions of humic acid in plants

Humic acid influences plants through multiple interconnected mechanisms. At its core, HA acts as a plant biostimulant, promoting improved nutrient acquisition, enhanced root and shoot growth, and overall stress resilience, independent of nutrient content (Canellas *et al.*, 2015). These effects are observed through indirect mechanisms (e.g., soil conditioning) and direct interactions with plant physiological and biochemical systems. The multifunctionality of HA arises from its complex molecular structure, which includes several functional groups (Fig. 1). These reactive functional groups are central to its biological activity and explain its diverse impacts on plant system permeability (Muscolo *et al.*, 2013; Olaetxea *et al.*, 2020).

One of the most widely recognised functions of HA is its ability to stimulate vegetative and reproductive growth. HA promotes root hair elongation and proliferation, leading to an expanded and more efficient root system. This increase in root surface area allows plants to extract more water and nutrients from the soil. The functional groups in HA enhance CEC and stimulate the uptake of essential nutrients by forming soluble chelates with metal ions, such as Fe, Zn and Mn (Ma *et al.*, 2024). Additionally, HA activates plasma membrane H^+-ATPase activity, which enhances ion transport and nutrient uptake, particularly for N, P, K, Ca and micronutrients (Tavares *et al.*, 2019). These processes collectively contribute to an increase in chlorophyll content, photosynthetic rate and dry matter accumulation, which ultimately translates to improved crop yield.

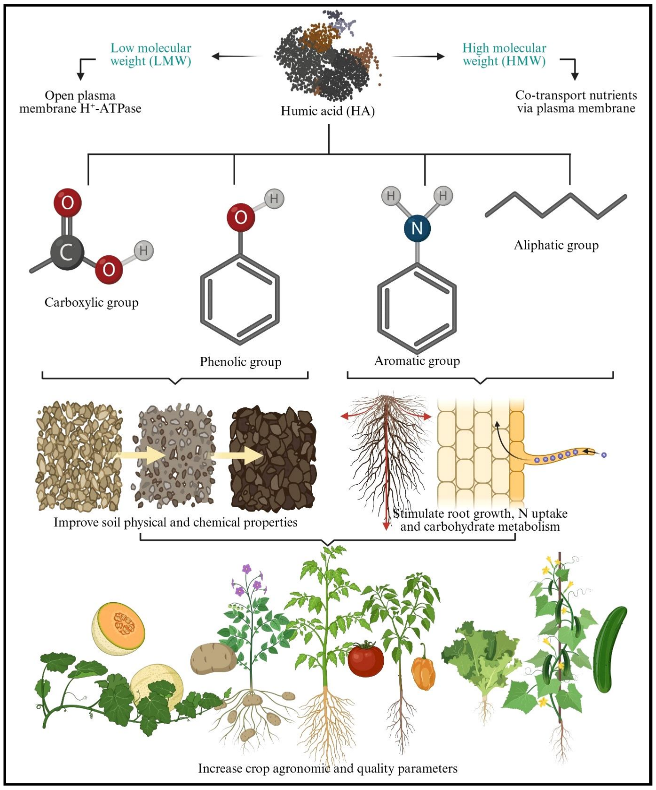

Fig. 1: An illustration of the structural components and functions of humic acid.

In vegetable crops, HA applications, whether as soil amendments or foliar sprays, have consistently shown beneficial impacts on yield components, such as greater fruit set, improved yield and higher biomass production. These yield responses are often more pronounced when HA is applied during critical growth stages such as vegetative expansion and flowering. The role of phenolic and aliphatic constituents of HA in modulating hormonal activity (auxin-like effects) may further enhance growth-promoting responses (Canellas and Olivares, 2014).

In addition to growth and yield, HA contributes significantly to crop quality by enhancing the accumulation of beneficial phytochemicals and nutrients. In several studies, HA application resulted in elevated levels of sugars, vitamins (e.g., ascorbic acid), proteins and phenolic compounds in harvested produce (García *et al.*, 2012; Wen *et al.*, 2024). The enhancement in fruit and vegetable quality can be attributed to improved nutrient uptake, higher metabolic activity and HA-induced modulation of gene expression associated with primary and secondary metabolism. HA's quinone and phenolic groups are known to influence redox signalling and activate secondary metabolite biosynthesis pathways, which are crucial for quality attributes such as flavour, aroma and antioxidant properties (Nabi *et al.*, 2025).

Humic acid also plays a critical role in protecting plants against abiotic stresses such as drought, salinity, extreme temperatures and heavy metal toxicity. Under drought and salinity stress, HA-treated plants show improved water-use efficiency, higher relative water content and better osmotic regulation due to increased accumulation of compatible solutes, such as proline and soluble sugars. These effects are linked to the ability of HA to improve root architecture, which is mediated by its hormone-like activity, and to retain soil moisture through its hydrophilic functional groups (Nabi *et al.*, 2025). HA maintains ion homeostasis by facilitating selective ion uptake and exclusion, particularly by increasing the K^+/Na^+ ratio in salt-stressed plants (Abu-Ria *et al.*, 2025). During temperature stress, HA has been shown to induce heat shock proteins (HSPs) and enhance the activities of antioxidant enzymes (e.g., SOD, CAT and POD), which are essential for maintaining protein structure and cellular integrity (Cha *et al.*, 2020). The phenolic and quinone groups in HA act as potent antioxidants, directly scavenging reactive oxygen species (ROS) generated under stress conditions (Kaya *et al.*, 2020; Nabi *et al.*, 2025). In heavy metal-contaminated environments, HA binds toxic ions (e.g., Cd, Pb and As) through chelation by carboxyl and phenolic groups, thereby reducing their bioavailability and translocation into plant tissues.

Table 1: Scientific reports published in the last eight years (2018-2025) on the effect of HA on growth and yield parameters of vegetable crops.

Crop	Assay	Dosage	Application	Main effect(s)	Reference
Chilli	F	80 g/plant	Soil	↑ plant height and stem diameter	(Sulistyono *et al.*, 2025)
Garlic	F	10 kg/ha	Soil	Superior effects on vegetative growth and yield characteristics; 17.95% more yield than the control	(Al-Mharib *et al.*, 2025)
Okra	F	3 g/L	Soil	Maximum plant height (163.33 cm), no. of main branches (9.29), leaf area (301.8 cm^2), no. of flowers (96.50), no. of pods (81.41), average yield per plant (350.50 g) and total yield (11.68 t/ha)	(Jassim and Hanshal, 2025)
Tomato	G	1.5 g/L	Soil	↑ vegetative growth, production of more fruits per plant with heavier fresh weight	(Alenazi and Khandaker, 2024)
Bok choy and red leaf lettuce	G	2%	Foliar spray	↑ plant morphological traits, leaf area index and biomass production	(Anandakumar *et al.*, 2024)
Broccoli	F	100 kg/ha	Soil	↑ growth and yield characteristics compared to the control	(Farhan *et al.*, 2023)
Bitter gourd	F	7 kg/ha	Soil	Highest plant height (175.6 cm), no. of leaves (37.2), no. of fruits (11.8), fruit length (26.97 cm), fruit diameter (5.71 cm), fruit weight (320.17 g), fruit weight per plant (1145.55 g) and total fruit weight after harvest (10.31 kg)	(Widari, 2024)
Ridge gourd	F	112 kg/ha	Soil	↑ growth, yield and yield attributing parameters; the total yield was 81.48% and 41% higher in contrast to the control and recommended practices	(Bordolui and Mandal, 2024)
Cabbage	F	3 mL/L	Foliar spray	Maximum number of leaves, stem weight, height and diameter, plant height, height diameter and weight, and total yield	(Mubarak *et al.*, 2023)
Radish	G	75 kg/ha	Soil	Significant enhancements in the growth and yield characteristics	(Hussain *et al.*, 2023)
Lettuce	F	30 L/ha	Soil	↑ plant growth	(Ekbic and Köse, 2022)
Tomato and melon	F	0.2%	Soil	Greatest increase in growth compared to the control	(Dunoyer *et al.*, 2022)
Faba bean	F	200 and 300 mg/L	Foliar spray	Application of HA @200 mg/L resulted in the highest plant height, seed yield and harvest index, while treatment with HA @300 mg/L produced the maximum biological yield	(Roudgarnejad *et al.*, 2021)
Spinach	G	3 mL/L	Soil	Highest leaf number (4.6) and biomass (150 mg)	(Naseri *et al.*, 2021)
Chilli	F	50 g/L	Foliar spray	↑ growth and yield, with 19.09% increment in total fruit yield compared to the control	(Jan *et al.*, 2020)

↑ Increased, *F* Field, *G* Greenhouse, *HA* Humic acid

Concurrently, HA upregulates antioxidant defense systems, minimises ROS accumulation and stabilises cellular membranes, mitigating oxidative damage (Wu *et al.*, 2017).

These combined actions, rooted in the structural chemistry of HA, allow vegetable crops to maintain productivity and quality under optimal as well as challenging environmental conditions. Overall, HA serves as a versatile tool for enhancing plant growth, development, yield and quality, while simultaneously providing resilience against multiple abiotic stresses (Fig. 2). This makes HA an essential component of sustainable vegetable crop production, particularly in stress-prone environments.

Effects of humic acid application on vegetable crops

Growth and yield

The effects of HA on the growth and yield

Table 2: Scientific reports published in the last eight years (2018-2025) on the effect of HA on quality attributes of vegetable crops.

Crop	Assay	Dosage	Application	Main effect(s)	Reference
Pea	F		Soil + foliar spray	↑ protein (24.2%) and micronutrients: Fe (390 ppm), Mn (79.5 ppm), Cu (55.1 ppm) and Zn (33.4 ppm)	(Lalkhumliana *et al.*, 2025)
Sweet pepper	G	0.03% Humistar (13.2% HA)	Foliar spray	↑ pericarp thickness (+36.6%), “! water loss (2% vs 5.2% in control) and ‘! phenolics post-storage (14.3%)	(Zamljen *et al.*, 2025)
Tomato	F	90 mg/L	Foliar spray	↑ lycopene (4.72 mg/100 g), vitamin C (16.93 mg/ 100 g), total sugar (5.68%), TSS (4.75 °Brix), shelf life (26.23 days), protein and Na^+ (7.28 mg/100 g)	(Ride *et al.*, 2024)
Bok choy and red leaf lettuce	G	2%	Foliar spray	↑ total chlorophyll (51.06, 45.67 SPAD), ascorbic acid (21.75, 18.35 mg/100 g) and phenols	(Anandakumar *et al.*, 2024)
Cucumber	G	200 mg/L	Foliar spray	Highest total phenol (1.99 mg/g FW), flavonoids (0.486 mg/g FW), proteins (34.56 mg/g FW), proline (3.86 µg/g FW) and soluble carbohydrates (30.80 mg/g FW)	(Amerian *et al.*, 2024)
Rocket	G	600 ppm	Nutrient solution	↑ vitamin C (730.7 mg/kg FW), phenols (1129 mg GAE/kg FW), flavonoids (1133 mg catechin/kg FW), antioxidant capacity (74.75%) and carbohydrates (46.99 mg/g)	(Sarabi, 2024)
Broccoli	F	60 Mg/ha	Soil	↑ N, P, K and Fe (4.25, 0.37 and 3.53 g/100 g and 201.80 mg/kg, respectively) and protein (24.87%) in head	(Abdulla and Esmai, 2023)
Okra	F	15 mL/L	Soil + foliar spray	Maximum TSS (2.28 °Brix)	(Pasha *et al.*, 2022)
Onion	G	100 mg/kg	Soil	↑ leaf vitamin C, Ca, Zn and K content, bulb flavonoids and total phenols	(Forotaghe *et al.*, 2022)
Radish	F	1.5 kg/ha	Soil	↑ root firmness, vitamin C, anthocyanin content, TSS and macronutrients: Mg, P, K, N and Ca	(Barzegar *et al.*, 2022)
Tomato	F	1000 mg/L	Foliar spray	↑ N, P and K concentration (2.21%, 0.23% and 1.51%, respectively), TSS (5.03 °Brix) and vitamin C (2.66 mg/100 g) in fruits	(Aboohanah *et al.*, 2021)
Spinach	G	3 mL/L	Soil	Highest chlorophyll a (1.8 mL/g fresh leaf), chlorophyll b (2.5 mL/g fresh leaf) and carotenoids (7.1 mL/g fresh leaf)	(Naseri *et al.*, 2021)
Red amaranth	G	20 mg/L	Soil	Maximum total chlorophyll, betanin and is obetanin content; lowest oxalate content	(Lestari *et al.*, 2020)

↑ Increased, *F* Field, *G* Greenhouse, *HA* Humic acid

characteristics of vegetable crops, including plant height, shoot and root length and weight, number and area of leaves, dimensions of the edible part (fruit/root/leaf) and total yield of the produce, have been assessed in a number of studies (Table 1). Vegetative parameters, such as plant height and number of leaves determine the plant growth, which ultimately has a direct effect on crop yield (Fig. 2). The yield component, determined in terms of various parameters, such as the number of fruits per plant and dry matter, is crucial to consider because it ultimately determines the profitability of the crop. The application of HA has been shown to enhance the production of plant growth-promoting hormones, such as auxins and cytokinins, and metabolic enzymes, which stimulate root and shoot growth (Olaetxea *et al.*, 2020). It also improves the uptake of macro-and micronutrients from the soil and increases the chlorophyll concentration in leaves (Sible *et al.*, 2021). The synthesis of plant hormones and enzymes, as well as the increase in biomass production, chlorophyll content and photosynthetic rate following HA application, have been shown to improve crop yields (Ampong *et al.*, 2022).

For example, El-Helaly (2018) observed increased root weight, root diameter, yield and harvest index of carrot with foliar spray of humic acid (1 g/L) compared to fulvic acid (0.5 g/L). Although both foliar and soil application of HA had a significant effect on growth and yield of lettuce, the best results (highest fresh weight and yield) were obtained with soil application of HA @1.5 mL/L (Raheem *et al.*, 2018). In contrast, numerous studies have demonstrated that the application of HA with mineral fertilisers, biofertilisers, or plant growth-promoting bacteria results in the delayed release of complex nutrients, which aids in subsequent nutrient absorption and promotes healthy growth, development and yield (de Moura *et al.*, 2023; Olaetxea *et al.*, 2020). For instance, a combination of biofertiliser (20 g/L) and HA (10 mL/L) resulted in the highest head weight and marketable yield compared to biofertiliser alone (Al-Taey *et al.*, 2019). Significant improvements (close to 30%) in plant growth and yield were noted in cauliflower following a combined foliar application of HA @4 mL/L and nanocalcium @2 mL/L (Rachid *et al.*, 2020).

Quality

The different effects of HA on the quality of vegetable crops are summarised in Table 2. The application of HA has been known to significantly improve the quality characteristics, including total soluble solids, total acidity, lycopene and nutritional content such as N, P, K, Ca and Mg in vegetable crops (Chandrakant and Verma, 2023). The application of HA improved early growth and bulb yield, as well as the sugar, protein and leaf soluble sugar contents of onion bulbs (Forotaghe *et al.*, 2021). In tomatoes, the highest fruit quality attributes, such as firmness, TSS, vitamin C, anthocyanin, and potassium, were recorded with the application of HA @3 g/L (Chah-Nasir *et al.*, 2023). The TSS (6.02%), ascorbic acid (39.85 mg/100 g) and lycopene content (93.75 mg/100 g) were recorded highest with the soil and foliar application of HA in the same crop (Kumar *et al.*, 2017). The quality attributes of melon fruits, *viz.* TSS, citric acid content, soluble dry matter and carbohydrates, were significantly enhanced following the application of 150 g/ha of HA (Dinu *et al.*, 2019). In a greenhouse experiment conducted for quality analysis based on TSS, titratable acidity and sugar-acid ratio (SAR), Sun *et al.*, (2022) reported that, at a dosage of 3000 kg/ha, HA application resulted in the best flavour of cherry tomatoes compared to farmyard manure (FM) and commercial organic fertiliser (COF). El-Gazzar *et al.*, (2020) concluded that the employment of HA @4 kg in combination with organic manures was more effective in increasing the reducing, non-reducing and total sugar percentages of watermelon fruit.

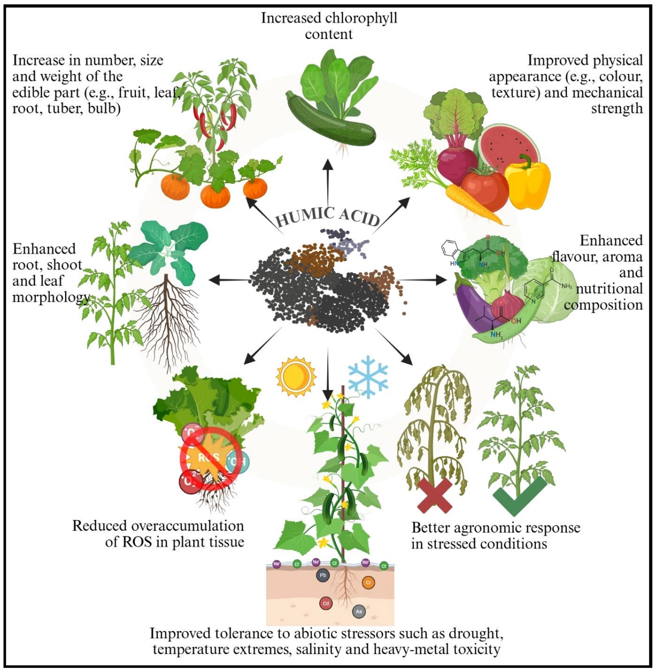

Fig. 2: Schematic representation of the main agronomic, biochemical and physiological effects of humic acid (HA) application on vegetable crops.

Humic acid (HA) has been shown to have a positive effect on increasing photosynthesis, ultimately resulting in increased chlorophyll content in leaves (Fig. 2). For instance, Hudda *et al.*, (2020) observed increased chlorophyll content (and hence, an increase in green colour) in pepper fruits as a result of HA application. A similar effect was observed in the okra cv. Arka Anamika due to the accelerated NO_3^- uptake that enhanced N metabolism and production of proteins, which ultimately increased the chlorophyll content in the leaves (Pasha *et al.*, 2021). In another study, Mohaseb *et al.*, (2018) reported that the application of HA positively influenced the total chlorophyll, vitamin C, starch and protein content of potatoes. Obaid *et al.*, (2020) stated that the application of HA @1.5 g/L resulted in the maximum recorded values for quality indicators, viz. chlorophyll and dry matter content in leaves and curd, of cauliflower. In a similar study conducted by Hawall *et al.*, (2018), the maximum levels of TSS and chlorophyll in broccoli were recorded following the foliar application of HA @3.5 mL/L.

Abiotic stress tolerance

The different effects of HA on abiotic stress tolerance in vegetable crops have been summarised in Table 3. Photosynthetic characteristics, such as leaf soil plant analysis development (SPAD) value, net photosynthetic rate, transpiration rate and intercellular CO_2 concentration,

Table 3: Scientific reports published in the last eight years (2018-2025) on the mitigation effect of HA against different abiotic stressors in vegetable crops.

Crop	Assay	Dosage	Appli-cation	Main effect(s)	Reference
Drought					
Tomato	G	3 mL/L	Foliar spray	↑ chlorophyll content and relative water content, and reduced ion leakage, MDA and proline content	(Aytaç *et al.*, 2024)
Broccoli	F	9.6 kg/ha	Soil	↑ vegetative growth and yield attributes, nutrient content and water use efficiency (WUE)	(Ibrahim *et al.*, 2024)
Fava bean	F	10 kg/ha	Soil	↑ cell membrane stability, photosynthetic pigments, osmoprotective activity and nutrient absorption	(Ramadan *et al.*, 2023)
Onion	G	100 mg/kg	Soil	↑ growth, physiological and biochemical traits of onion leaves and bulbs	(Forotaghe *et al.*, 2021)
Potato	G	4.5 L/ha	Soil	63.48% increase in yield compared to control and improved photosynthetic parameters	(Man-hong *et al.*, 2020)
Extreme temperature					
Melon	G	300 mg/L	Seedling treatment	↑ plant height, stem diameter, fresh and dry weight, chlorophyll content, root architecture, SOD and CAT activity	(Zhu *et al.*, 2024)
Tomato	Lab	500 mg/L	Substrate	↑ vegetative growth and chlorophyll fluorescence, antioxidant enzymes and expression of genes related to thermal tolerance	(Han *et al.*, 2023)
Zucchini	Lab	0.05%	Seedling treatment	↑ activities of SOD and CAT, and the contents of soluble sugar, chlorophyll and proline	(Li *et al.*, 2023)
Salinity					
Chilli	G	200 mg/kg soil	Soil	↑ biomass, photosynthetic pigment levels and enzymatic activity	(Zohaib *et al.*, 2024)
Bean	F	30 ìL/kg soil + 0.2% HA	Soil + foliar spray	↑ microelement uptake, relative water content and turgor pressure, and reduced oxidative damage	(Kutlu and Gulmezoglu, 2023)
Lettuce	SL	400 mg/L	Nutrient solution	Maximum head diameter, fresh head weight, dry head weight and yield, increased leaf nutrient, total carbohydrates and vitamin C content	(ElFayomy *et al.*, 2021)
Onion	G	1.0 g/kg	Substrate	↑ plant growth and nutrient content, and reduced Na^+ toxicity	(Turhan *et al.*, 2020)
Heavy metal toxicity					
Brinjal	G	500 mg/kg soil	Soil	↑ growth, fruit quality and antioxidant capacity	(Sayed *et al.*, 2024)
Lettuce	G	10%	Soil	↑ plant biomass and restricted Cr accumulation and its transfer from soil to leaves	(Omidi *et al.*, 2023)
Pumpkin	Lab	400 mg/L	Substrate	↑ seed vigour, seed germination and antioxidant enzyme activity, and reduced Cd uptake by seeds	(Asadi Aghbolaghi *et al.*, 2022)

↑ Increased, *F* Field, *G* Greenhouse, *HA* Humic acid, *Lab* Laboratory, *SL* Soilless system

play a key role in crop productivity and are closely related to yield (Iqbal and Ashraf, 2013; Long *et al.*, 2015). However, these parameters are sensitive to unfavourable environmental conditions, such as drought, extreme temperatures and salinity, which significantly impact plant growth and development. These critical phases can be addressed and overcome by the application of HA, which can enhance different metabolic pathways in plants. Humic acid (HA) improves stress tolerance in plants by reducing the overaccumulation of reactive oxygen species (ROS) and malondialdehyde (MDA) content, thereby reducing plasma membrane permeability (García *et al.*, 2012; Muscolo *et al.*, 2013) (Fig. 2).

Yaquby *et al.*, (2024) demonstrated that the application of HA alone @2 g/L had a positive impact in minimizing the salinity stress and improving the growth attributes of cucumber, viz. seed vigour index, shoot length, root length etc. Similarly, in yellow hot chilli, the application of HA @1500 ppm along with a phytohormone substantially increased the yield by 82% by improving salt tolerance under salinity stress (Van and Di, 2022). The application of HA @400 ppm enhanced the leaf biomass in squash under salinity conditions (Al Gehani, 2020). These outcomes might be attributed to the role of HA in increasing the permeability of the cell membrane, absorption and transportation of nutrients, and preventing Na^+ uptake in the plant tissue. HA binds the elements and lowers soil pH; thus, the availability of many elements (N, P, K) increases at low pH, while that of nutrients such as Ca and Na is limited.Najafi *et al.*, (2021) observed that the utilization of HA alone @200 ppm improved the effects of drought stress in cucumber. HA plays a significant role in modifying physiological and biochemical processes (Ibrahim *et al.*, 2024), and increasing nutrient uptake and N, P and K content (Bhatt and Singh, 2022), all of which might have led to an enhanced photosynthetic rate and overall growth and yield of the plants under moisture-deficit conditions.

Similar to the stress imposed by drought, salt and extremely high and low temperatures, heavy metal-induced oxidative stress presents a significant challenge to plant growth and yield. However, HA has been proven to be highly effective in reducing these types of stressors owing to the presence of carboxylic and phenolic groups. These groups actively filter ROS that accumulate under heavy metal stress, functioning as potent natural antioxidants. In addition, HA also preserves cellular integrity and functionality by reducing oxidative damage to dynamic cellular components, such as lipids, proteins and nucleic acids, by the neutralisation of ROS (Nabi *et al.*, 2025). The soil application of HA at a concentration of 250 mg/kg reduced cadmium (Cd) uptake in the roots and fruits of chilli by activating physio-biochemical defense mechanisms, thereby improving the plant's tolerance to heavy metal stress and simultaneously increasing dry biomass content, yield and quality. Similarly, Wen *et al.*, (2024) assessed the toxicity of arsenate in lettuce using a combination of pyrite and HA and concluded that the combined application of pyrite and HA promoted plant growth to a certain extent and reduced As-induced phytotoxicity by increasing superoxide dismutase (SOD) content and decreasing malonaldehyde (MDA) content.

The inconsistent findings in the aforementioned studies demonstrate that recommendations for the application of HA to enhance crop agronomic performance can only be reliable after testing under certain circumstances. According to research, application of HA and mineral fertilisers together creates complexes that release nutrients gradually and aid in crop uptake. However, this interaction largely depends on the crop type, the HA source and the application rate (Rose *et al.*, 2014). Therefore, it is essential to determine the optimal application rates for a certain HA source on crop agronomic parameters in numerous crops under specific growing conditions.

Factors affecting efficiency of humic acid

Source of HA

The effectiveness of HA on vegetable crops varies significantly depending on the source. Several factors, including nutritional composition, production method, functional group composition and intended application, influence the effects of HA (Gollenbeek and van der Weide, 2020). Studies have ranked different HA sources based on their effectiveness in improving crop agronomic parameters, with compost from manure and green waste showing higher efficacy than soil, brown coal and peat (Rose *et al.*, 2014). Commercially produced HA generally exhibits lower effectiveness than that derived from waste materials. Compost-derived HA has been shown to be particularly effective in boosting plant physiological activities (Jindo *et al.*, 2020). Functional group analysis revealed that HA containing high levels of carboxylic groups tended to enhance nitrogen uptake, whereas those rich in aromatic groups exhibited reduced fungicidal properties (Wei *et al.*, 2018). Further research is needed to comprehensively assess and compare the effects of different HA sources under field and laboratory conditions (Laskosky *et al.*, 2020).

Application rate of HA

The growth, yield and physical fruit traits of three sweet pepper cultivars showed higher values with increased HA application rates (Ibrahim *et al.*, 2019). Humic acid (HA) application rates are generally more effective under stress conditions, although responses vary by crop and HA source (Olk *et al.*, 2018; Rose *et al.*, 2014). Under salt stress, HA enhanced growth and proline content of beans, with effects increasing with the application rate (Taha and Osman, 2018). Similarly, with higher application rates of HA, potato tubers recorded higher starch content, total protein content and total yield under drought stress (Koheal *et al.*, 2025), and pepper plants showed increased levels of N, P and K under salt stress conditions (Akladious and Mohamed, 2018). However, there are cases where typical application rates of HA did not elicit a significant agronomic response (Hartz and Bottoms, 2010).

Soil type

Soil type plays a crucial role in the adsorption, retention and decomposition of HA, thereby influencing its effectiveness. Efficient HA use requires that it remains in the soil without leaching (Chen *et al.*, 2017). Sandy soils, due to their coarse texture and poor structure, have low nutrient and amendment retention capacity (Sarlaki *et al.*, 2021). In contrast, clay fractions vary among soils and significantly influence HA binding capacity (Singh *et al.*, 2017). Among clay minerals, kaolinite, a 1:1 clay, has a higher HA adsorption capacity than montmorillonite, as shown by Al-Essa (2019) and Chen *et al.,* (2017), due to its distinct physical and chemical traits. Consequently, the variability in clay mineral composition across soils influences HA performance and its impact on soil properties and crop productivity. Faba bean, for instance, responded better to HA in non-calcareous soil than in calcareous soil (Farid *et al.*, 2021).

Key knowledge gaps

While the benefits of humic acid (HA) application in agriculture are increasingly recognised, several knowledge gaps continue to limit its broader adoption in vegetable production systems. Especially, majority of the studies highlighting the positive effects of HA have been conducted in controlled environments such as greenhouses or laboratories. As a result, their applicability under field conditions remains uncertain, particularly in different soil types, cropping systems and agroclimatic zones. There is a need for long-term, multi-location field trials involving vegetable crop rotations that assess the performance of HA with varying N sources and under changing climatic scenarios. Another underexplored area is the precise contribution of the structural and molecular characteristics of HA, such as solubility, molecular weight and the density of functional groups, to its biological efficacy. These traits likely determine how HA interacts with soil particles, plant roots and microbial communities, yet few studies have examined them in context-specific field applications. Moreover, the differential roles of water-soluble and alkaline-soluble fractions of HA in shaping crop yield and soil health remain largely unexplored. Additionally, little is known about how HA influences nutrient synchronisation between soil availability and plant uptake under real-time growth conditions. Questions also remain regarding the ability of HA to modulate enzymatic activity and microbial biomass in the rhizosphere. Addressing these research needs will be essential for developing precise, crop-specific HA formulations and management strategies.

Future prospects

Future research should focus on deciphering the specific molecular mechanisms underlying HA-induced physiological responses, particularly under varying agroclimatic conditions. The development of crop-specific HA formulations, enriched with biofertilisers, micronutrients, or nanomaterials, may further enhance its efficacy while reducing dependence on synthetic inputs. Studies should also prioritize optimizing HA dosages, modes of application and timing to align with critical growth stages of different vegetable species. Moreover, long-term field trials and meta-analyses are essential to quantify the cumulative benefits of HA on soil health, nutrient cycling and carbon sequestration under integrated nutrient management (INM) systems. Investigating the role of HA as a carrier for microbial inoculants or as a priming agent in seed treatment offers promising avenues. Finally, large-scale production of high-quality HA from sustainable sources will be crucial for mainstreaming its use in commercial vegetable farming. Collectively, these efforts will help translate the full agronomic potential of humic acid into resilient and resource-efficient vegetable production systems.

Conclusion

Humic acid (HA) offers significant potential for enhancing vegetable crop production. Its application improves agronomic aspects such as growth, development and yield, along with quality attributes. It is also effective in mitigating abiotic stresses. The diverse effects of HA on vegetable crops can be attributed to its complex structure and varying sources. Even within the same crop species, responses to HA can differ based on the origin of the material, application dose, timing relative to plant phenology, frequency of application, and environmental and experimental conditions. Some studies report greater efficacy at higher doses, while others find lower doses more beneficial. While both the methods enhance productivity, some findings favour soil application, others support foliar spraying, and several suggest a synergistic effect when both are combined. By reducing the required fertiliser doses, HA contributes to cost-effective cultivation practices for farmers.

Conflict of interest: The authors declare no conflict of interest.

References

Abdulla, A.A. and Esmai A.O. (2023). Combination influence of humic acid and chelated iron on yield and quality of broccoli (*Brassica oleracea* L.) in Erbil, Iraqi Kurdistan region. *Zanco Journal of Pure and Applied Sciences*, **35(1)**, 126-135.

Aboohanah, M.A., Salman J.A.A. and Hnoosh L.J.H. (2021). Effect of spraying putrescine and humic acid spraying on chemical parameters of tomato plant *Lycopersiconesculentum*. *Scientific Papers. Series B, Horticulture*, **65(2)**, 137-142.

Abu-Ria, M., Shukry W., Abo-Hamed S., Albaqami M., Almuqadam L. and Ibraheem F. (2023). Humic acid modulates ionic homeostasis, osmolytes content, and antioxidant defense to improve salt tolerance in rice. *Plants*, **12(9)**, 1834.

Akladious, S.A. and Mohamed H.I. (2018). Ameliorative effects of calcium nitrate and humic acid on the growth, yield component and biochemical attribute of pepper (*Capsicum annuum*) plants grown under salt stress. *Scientia Horticulturae*, **236**, 244-250.

Al Gehani, I.A. (2020). Physiological Responses of Squash (*Cucurbita pepo* L.) to Humic Acid Treatment under NaCl Stress Conditions. *Scientific Journal of University of Benghazi*, **33(2)**, 6-6.

Alenazi, M.M. and Khandaker M.M. (2021). Responses of tomato hybrid cultivars to soil application of humic acid under greenhouse conditions. *Brazilian Journal of Biology*, **84**, e252573.

Al-Essa, K. (2019). Adsorption of humic acid onto kaolinite clay: a mini-review. *Journal of Chemical Science and Engineering*, **2**, 53-57.

Al-Mharib, M.Z.K., Al-Zaidi A.K.N. and Al-Quraishi I.A.A. (2025). Effect of adding humic acid and potassium fertilizer on growth and yield of garlic plants.*IOP Conference Series: Earth and Environmental Science*, **1487(1)**, 012037.

Al-Taey, D.K., Al-Shareefi M.J., Mijwel A.K., Al-Tawaha A.R. and Al-Tawaha A.R. (2019). The beneficial effects of bio-fertilizers combinations and humic acid on growth, yield parameters and nitrogen content of broccoli grown under drip irrigation system. *Bulgarian Journal of Agricultural Science*, **25(5)**, 959-966.

Amador, H.V., Izquierdo F.G. and Padrón V.V. (2018). Humic substances as plant biostimulants under environmental stress conditions. *Tropical Crops*, **39(4)**, 102-109.

Amerian, M., Palangi A., Gohari G. and Ntatsi G. (2024). Humic acid and grafting as sustainable agronomic practices for increased growth and secondary metabolism in cucumber subjected to salt stress. *Scientific Reports*,**14(1)**, 15883.

Ampong, K., Thilakaranthna M.S. and and Gorim L.Y. (2022). Understanding the role of humic acids on crop performance and soil health. *Frontiers in Agronomy*, **4**, 848621.

Anandakumar, S., Ranjith S., Senthamilselvi D., Rajadurai G. and Sivakumar K. (2024). Foliar application of humic acid on growth and biomass improvement of bok choy and red leaf lettuce. *Plant Science Today*, **11(2)**, 21-28.

Asadi Aghbolaghi, M., Sedghi M., Sharifi R.S., Dedicova B. (2022). Germination and the biochemical response of pumpkin seeds to different concentrations of humic acid under cadmium stress. *Agriculture*, **12(3)**, 374.

Aytaç, E., Ünlü H., Erkan Ý.E. and Akçay U.Ç. (2024). Humic acid mitigates drought stress in tomato. *Bilge International Journal of Science and Technology Research*, **8(1)**, 27-37.

Barzegar, T., Mahmoodi S., Nekounam F., Ghahremani Z., Khademi O. (2022). Effects of humic acid and cytokinin on yield, biochemical attributes and nutrient elements of radish (*Raphanussativus* L.) cv. Watermelon. *Journal of Plant Nutrition*, **45(10)**, 1582-1598.

Bhatt, P. and Singh V.K. (2022). Effect of humic acid on soil properties and crop production - A review. *Indian Journal of Agricultural Sciences*, **92(12)**, 1423-1430.

Billingham, K.L. (2020). Humic products - Potential or presumption for agriculture. Do humic products have a place in Australian grazing enterprises?. *IGC Proceedings* (1989-2023), **3**, 1485-1486.

Bordolui, S.K. and Mandal G.S. (2024). Influence of humic acid on yield and yield attributing characters of ridge gourd. *American International Journal of Agricultural Studies*, **9(1)**, 27-34.

Canellas, L.P. and Olivares F.L. (2014). Physiological responses to humic substances as plant growth promoter. *Chemical and Biological Technologies in Agriculture*, **1(1)**, 3.

Canellas, L.P., Olivares F.L., Aguiar N.O., Jones D.L., Nebbioso A., Mazzei P. and Piccolo A. (2015). Humic and fulvic acids as biostimulants in horticulture. *Scientia Horticulturae*, **196**, 15-27.

Cha, J.Y., Kang S.H., Ali I., Lee S.C., Ji M.G., Jeong S.Y., Shin G.I., Kim M.G., Jeon J.R. and Kim W.Y. (2020). Humic acid enhances heat stress tolerance via transcriptional activation of heat-shock proteins in Arabidopsis. *Scientific Reports*, **10(1)**, 15042.

Chah-Nasir, A.S., Jahromi A.A., Behrooznam B., Khankahdani H.H. and Ejraei A. (2023). Effect of humic acid and amino acid foliar applications on the growth characteristics, yield, and fruit quality of tomato (*Solanum lycopersicum* L.). *International Journal of Horticultural Science and Technology*, **10(3)**, 309-318.

Chandrakant, P.M. and Verma D. (2023). Effect of humic acid on vegetable crops - A review. *Environment and Ecology*, **41(4A)**, 2440-2445.

Chen, H., Koopal L.K., Xiong J., Avena M. and Tan W. (2017). Mechanisms of soil humic acid adsorption onto montmorillonite and kaolinite. *Journal of Colloid and Interface Science*, **504**, 457-467.

de Aguiar, T.C., de Oliveira Torchia D.F., de Castro T.A., Tavares O.C., de Abreu Lopes S., da Silva L.D., Castro R.N., Berbara R.L., Pereira M.G. and García A.C. (2022). Spectroscopic-chemometric modeling of 80 humic acids confirms the structural pattern identity of humified organic matter despite different formation environments. *Science of the Total Environment*, **833**, 155133.

de Castro, T.A.V.T., Berbara R.L.L., Tavares O.C.H., da Graca Mello D.F., Pereira E.G., de Souza C.D.C.B., Espinosa L.M. and García A.C. (2021). Humic acids induce a eustress state via photosynthesis and nitrogen metabolism leading to a root growth improvement in rice plants. *Plant Physiology and Biochemistry*, **162**, 171-184.

de Melo, B.A., Motta F.L. and Santana M.H. (2016). Humic acids: Structural properties and multiple functionalities for novel technological developments. *Materials Science and Engineering: C*, **62**, 967-974.

de Moura, O.V.T., Berbara R.L.L., de Oliveira Torchia D.F., Da Silva H.F., de Castro T.A.V.T., Tavares O.C.H., Rodrigues N.F., Zonta E., Santos L.A., García A.C. (2023). Humic foliar application as sustainable technology for improving the growth, yield, and abiotic stress protection of agricultural crops. A review. *Journal of the Saudi Society Agricultural Sciences*, **22(8)**, 493-513.

Dinu, M., Soare R., Babeanu C., Hoza G. and Apahidean A.I. (2019). Effect of organic fertilization on the quantity and quality of melon production.*Carpathian Journal of Food Science & Technology*, **11(2)**, 177-184.

Dunoyer, A.A.T., Castillo F.C. and Camargo J.M. (2022). Effect of humic acid on the growth of seedling tomato (*Solanum lycopersicum*) and melon *Cucumismelo*. *Revista Ambiente & Água*, **17(4)**, e2808.

Ekbiç, E. and Köse M.A. (2022). Effects of humus and humic acid on plant growth and nutritional uptake of lettuce (*Lactuca sativa* L.). *Applied Ecology & Environmental Research*, **20(3)**, 2261-2269.

ElFayomy, A., Yousry M.M. and El-Behairy U.A. (2021). Response of lettuce to humic acid and salt stress condition under soilless culture system. *Journal of the Advances in Agricultural Researches*, **26(1)**, 20-38.

El-Gazzar, T.M., Tartoura E.A., Farid S.E., Zake M.N. and Ebrahim Y.M. (2020). Effect of different sources of organic manures and different levels of humic and fulvic acid on growth, flowering, yield and its components of watermelon plants. *Journal of Plant Production*, **11(11)**, 1135-1143.

El-Helaly, M.A. (2018). Effect of foliar application of humic and fulvic acids on yield and its components of some carrot (*Daucus carota* L.) cultivars. *Journal of Horticultural Science &Ornamental Plants*, **10(3)**, 159-166.

Farhan, K.J., Mahdi L.E., Al-Falahi M.N., Sallume M.O. and Alkhateb B.A. (2023). The role of iron nanoparticles and humic acid in iron concentration, growth and yield of broccoli (*Brassicaoleracea* var. *italica*). *IOP Conference Series: Earth and Environmental Science*, **1158(2)**, 022033.

Farid, I.M., El-Ghozoli M.A., Abbas M.H.H., El-Atrony D.S., Abbas H.H., Elsadek M., Saad H.A., El Nahhas N. and Mohamed I. (2021). Organic materials and their chemically extracted humic and fulvic acids as potential soil amendments for faba bean cultivation in soils with varying $CaCO_3$ contents. *Horticulturae*, **7(8)**, 205.

Fischer, T. (2017). Humic supramolecular structures have polar surfaces and unipolar cores in native soil. *Chemosphere*, **183**, 437-443.

Forotaghe, Z.A., Souri M.K., Jahromi M.G., Torkashvand A.M. (2021). Physiological and biochemical responses of onion plants to deficit irrigation and humic acid application. *Open Agriculture*, **6(1)**, 728-737.

Forotaghe, Z.A., Souri M.K., Jahromi M.G. and Torkashvand A.M. (2022). Influence of humic acid application on onion growth characteristics under water deficit conditions. *Journal of Plant Nutrition*, **45(7)**, 1030-1040.

García, A.C., de Souza L.G., Pereira M.G., Castro R.N., García-Mina J.M., Zonta E., Lisboa F.J. and Berbara R.L. (2016). Structure-property-function relationship in humic substances to explain the biological activity in plants. *Scientific Reports*, **6(1)**, 20798.

García, A.C., Santos L.A., Izquierdo F.G., Sperandio M.V., Castro R.N., Berbara R.L. (2012). Vermicompost humic acids as an ecological pathway to protect rice plant against oxidative stress. *Ecological Engineering*, **47**, 203-208.

Gollenbeek, L. and van der Weide R. (2020). *Prospects for Humic Acid Products from Digestate in the Netherlands*. Report WPR-867, 5-40.

Hamad, M. and Tantawy M. (2018). Effect of different humic acids sources on the plant growth, calcium and iron utilization by sorghum. *Egyptian Journal of Soil Science*, **58(3)**, 291-307.

Han, L., Zhao Z., Li J., Ma X., Zheng X., Yue H., Sun G., Lin Z. and Guan S. (2023). Application of humic acid and hydroxyapatite in Cd-contaminated alkaline maize cropland: A field trial. *Science of the Total Environment*, **859**, 160315.

Hartz, T.K. and Bottoms T.G. (2010). Humic substances generally ineffective in improving vegetable crop nutrient uptake or productivity. *HortScience*, **45(6)**, 906-910.

Hawall, I.A., Sumaia M.R. and Ghuncha K.T. (2018). Growth and yield of broccoli (*Brassica oleracea* L. var. Corato) as affected by humic acid application. *Journal of Plant Production*, **9(9)**, 739-741.

Hudda, J., Godara A. and Kukreja S. (2020). Effect of application of humic acid and vermiwash on the growth, quality and yield of plants: A review. *International Journal of Current Microbiology and Applied Sciences*, **9(11)**, 1277-1284.

Hussain, K., Kiran M., Haq F., Waseem K., Nadeem M.A., Ullah G., Farid A. and Aziz T. (2023). Humic acid as a growth booster: Evaluating its synergistic influence on three red radish varieties. *Trends in Horticulture*, **6(1)**, 19-33.

Ibrahim, A., Abdel-Razzak H., Wahb-Allah M., Alenazi M., Alsadon A. and Dewir Y.H. (2019). Improvement in growth, yield, and fruit quality of three red sweet pepper cultivars by foliar application of humic and salicylic acids. *HortTechnology*, **29(2)**, 170-178.

Ibrahim, E.A., Ebrahim N.E. and Mohamed G.Z. (2024). Mitigation of water stress in broccoli by soil application of humic acid. *Scientific Reports*, **14(1)**, 2765.

Iqbal, M. and Ashraf M. (2013). Gibberellic acid mediated induction of salt tolerance in wheat plants: Growth, ionic partitioning, photosynthesis, yield and hormonal homeostasis. *Environmental and Experimental Botany*, **86**, 76-85.

Jan, J.A., Nabi G., Khan M., Ahmad S., Shah P.S. and Hussain S. (2020). Foliar application of humic acid improves growth and yield of chilli (*Capsicum annuum* L.) varieties. *Pakistan Journal of Agricultural Research*, **33(3)**, 461-472.

Jassim, A.N. and Hanshal M.A. (2025). Role of humic acid and magnesium on the growth of okra crop. *IOP Conference Series: Earth and Environmental Science*, **1487(1)**, 012108.

Jindo, K., Olivares F.L., Malcher D.J.P., Sánchez-Monedero M.A., Kempenaar C. and Canellas L.P. (2020). From lab to field: Role of humic substances under open-field and greenhouse conditions as biostimulant and biocontrol agent. *Frontiers in Plant Science*, **11**, 426.

Kaya, C., Senbayram M., Akram N.A., Ashraf M., Alyemeni M.N. and Ahmad P. (2020). Sulfur-enriched leonardite and humic acid soil amendments enhance tolerance to drought and phosphorus deficiency stress in maize (*Zea mays* L.). *Scientific Reports*, **10(1)**, 6432.

Koheal, H.K., El-Damarawy Y., El-Azab M., Essa I. and Aboud F.S. (2025). Enhancing potato productivity and nutritional status under drought stress: The role of humic acid in climate-resilient agriculture. *Egyptian Journal of Agronomy*, **47(2)**, 225-234.

Kumar, H., Kaushik R.A., Ameta K.D., Regar A.L., Singh K., Rajawat K.S. and Kumari P. (2017). Effect of humic acid and nutrients mixture on quality parameter of tomato (*Lycopersicon esculentum* Mill.) under polyhouse condition. *Journal of Applied and Natural Science*, **9(3)**, 1369.

Kutlu, I. and Gulmezoglu N. (2023). Suitable humic acid application methods to maintain physiological and enzymatic properties of bean plants under salt stress. *Gesunde Pflanzen*, **75(4)**, 1075-1086.

Lalkhumliana, F., Kaushal R., Ananthakrishnan S., Shankar V. and Lalrinzuali R.K. (2025). Evaluating the impact of PGPR and humic acid on soil properties and productivity of pea (*Pisum sativum*). *Journal of Plant Nutrition*, **10**, 1-21.

Laskosky, J.D., Mante A.A., Zvomuya F., Amarakoon I. and Leskiw L. (2020). A bioassay of long term stockpiled salvaged soil amended with biochar, peat, and humalite. *Agrosystems, Geosciences & Environment*, **3(1)**, e20068.

Lestari, F. and Dewi K. (2020). Effects of humic acid on vegetative growth, yield, oxalic acid and betacyanin content of red amaranth (*Amaranthus tricolor* L.). *AIP Conference Proceedings*, **2260(1)**, 030011.

Li, H., Kong F., Tang T., Luo Y., Gao H., Xu J., Xing G. and Li L. (2023). Physiological and transcriptomic analyses revealed that humic acids improve low-temperature stress tolerance in zucchini (*Cucurbita pepo* L.) seedlings. *Plants*, **12(3)**, 548.

Long, S.P., Marshall-Colon A. and Zhu X.G. (2015). Meeting the global food demand of the future by engineering crop photosynthesis and yield potential. *Cell*, **161(1)**, 56-66.

Ma, Y., Cheng X. and Zhang Y. (2024). The impact of humic acid fertilizers on crop yield and nitrogen use efficiency: A meta-analysis. *Agronomy*, **14(12)**, 2763.

Man-hong, Y., Lei Z., Sheng-tao X., McLaughlin N.B. and Jing-hui L. (2020). Effect of water soluble humic acid applied to potato foliage on plant growth, photosynthesis characteristics and fresh tuber yield under different water deficits. *ScientificReports*, **10(1)**, 7854.

Mirza, M.A., Agarwal S.P., Rahman M.A., Rauf A., Ahmad N., Alam A. and Iqbal Z. (2011). Role of humic acid on oral drug delivery of an antiepileptic drug. *Drug Development and Industrial Pharmacy*, **37(3)**, 310-319.

Mohaseb, M.I., Khafagy H.A., Mahrous M.S. and Abdel-azeem S.M. (2018). Effect of humic substances addition and foliar spraying with biostimulants on growth, yield and quality of potato (*Solanum tuberosum*). *Annals of Agricultural Science Moshtohor*, **56(4)**, 1121.

Mubarak, D.M., Yasser A., El-Azab M.E. and Aly M.M. (2023). Impact of spraying chelated zinc with humic acid extracted from compost on the growth, yield and nutritional status of Japanese cabbage plants grown in sandy soil. *European Journal of Biological Sciences*, **15(1)**, 1-7.

Muscolo, A., Sidari M. and Nardi S. (2013). Humic substance: Relationship between structure and activity. Deeper information suggests univocal findings. *Journal of Geochemical Exploration*, **129**, 57-63.

Nabi, F., Sarfaraz A., Kama R., Kanwal R. and Li H. (2025). Structure-based function of humic acid in abiotic stress alleviation in plants: A review. *Plants*, **14(13)**, 1916.

Najafi, M., Arouiee H. and Aminifard M.H. (2021). Effects of humic acid and amino acid on some growth traits on super daminus cucumber (*Cucumis sativus* L.) under drought stress. *Journal of Horticultural Science*, **35(4)**, fa521-fa533.

Nardi, S., Ertani A. and Francioso O. (2017). Soil-root cross talking: The role of humic substances. *Journal of Plant Nutrition and Soil Science*, **180(1)**, 5-13.

Nardi, S., Schiavon M. and Francioso O. (2021). Chemical structure and biological activity of humic substances define their role as plant growth promoters. *Molecules*, **26(8)**, 2256.

Naseri, M., Arouiee H. and Mohammadi M. (2021). The effect of concentration and time of application of humic acid on morpho-physiological characteristics of *Spinacia oleracea*. *Journal of Horticultural Science*, **34(4)**, 663-678.

Obaid, A.K., Hiji H.J. and Alamer Z. (2020). The effect of humic acid and high potassium on some growth characteristics and yield of cauliflower. *Plant Cell Biotechnology and Molecular Biology*, **21(67&68)**, 14-20.

Olaetxea, M., Mora V., Baigorri R., Zamarreño A.M. and García-Mina J.M. (2020). The singular molecular conformation of humic acids in solution influences their ability to enhance root hydraulic conductivity and plant growth. *Molecules*, **26(1)**, 3.

Olk, D.C., Dinnes D.L., Rene Scoresby J., Callaway C.R. and Darlington J.W. (2018) Humic products in agriculture: Potential benefits and research challenges-A review. *Journal of Soils and Sediments*, **18**, 2881-2891.

Omidi, A., Astaraei A.R. and Emami H. (2023). Evaluation of humic acid on chromium toxicity, accumulation and translocation in lettuce (*Lactucasativa* L. var. *longifolia*). *Journalof Horticultural Science*, **37(2)**, 541-560.

Pasha, N. and Kumari R.V. (2022). Effect of humic acid on growth, yield and quality of okra (*Abelmoschus esculentus* L.) cv. Arka Anamika. *Mysore Journal of Agricultural Sciences,* **56(1)**, 439.

Pasha, N., Vasanthakumari R., Hanamantharaya B.G., Nirmala K.S. and Vidya A. (2021). Effect of humic acid on growth of okra (*Abelmoschus esculentus* L.) cv. Arka Anamika. *International Journal of Current Microbiology and Applied Sciences*, **10(2)**, 3530-3534.

Rachid, A.F., Bader B.R. and Al-Alawy H.H. (2020). Effect of foliar application of humic acid and nanocalcium on some growth, production, and photosynthetic pigments of cauliflower (*Brassica oleracea* var. *botrytis*) planted in calcareous soil. *Plant Archives*, **20(1)**, 32-37.

Raheem, S.M., Al-Jaf H.I. and Tofiq G.K. (2018). Influence of foliar and soil application of humic acid on growth and yield of lettuce. *Journal of Biology, Agriculture and Healthcare*, **8(8)**, 1-4.

Ramadan, K.M., El-Beltagi H.S., El-Mageed T.A., Saudy H.S., Al-Otaibi H.H. and Mahmoud M.A. (2023). The changes in various physio-biochemical parameters and yield traits of faba bean due to humic acid plus 6-benzylaminopurine application under deficit irrigation. *Agronomy*, **13(5)**, 1227.

Ride, R.S., Ahmed S., Monami S.A. and Sarkar M.D. (2024). Improvement in growth, yield, and fruit quality of tomato by foliar application of humic and salicylic acids. *Notulae Scientia Biologicae*, **16(4)**, 12189.

Rose, M.T., Patti A.F., Little K.R., Brown A.L., Jackson W.R. and Cavagnaro T.R. (2014). A meta-analysis and review of plant-growth response to humic substances: Practical implications for agriculture. *Advances in Agronomy*, **124**, 37-89.

Roudgarnejad, S., Samdeliri M., Mirkalaei A.M. and Moghaddam M.N. (2021). The role of humic acid application on quantitative and qualitative traits of faba bean (*Vicia faba* L.). *Gesunde Pflanzen*, **73(4)**, 603-611.

Sarabi, B. (2024). Effect of nutrient solution concentrations and irrigation levels combined with humic acid on physiological and quality characteristics of rocket crop (*Eruca sativa* (Mill.) Thell.). *Arid Land Research and Management*, **38(2)**, 201-225.

Sarlaki, E., Paghaleh A.S., Kianmehr M.H. and Vakilian K. (2021). Valorization of lignite wastes into humic acids: Process optimization, energy efficiency and structural features analysis. *Renewable Energy*, **163**, 105-122.

Sayed, A.A.S., Seoudi Z., Osman A.S., Semida W.M., Rady M.M., Elkelish A. and Mahmoud A.E. (2024). Soil-plant integrative supplementation with humic acid and antioxidants improves growth, fruit quality, and antioxidant capacity of Cd-stressed *Solanum melongena*. *Journal of Soil Science and Plant Nutrition*, **24**, 7581-7604.

Sible, C.N., Seebauer J.R. and Below F.E. (2021). Plant biostimulants: A categorical review, their implications for row crop production, and relation to soil health indicators. *Agronomy*, **11(7)**, 1297.

Singh, M., Sarkar B., Hussain S., Ok Y.S., Bolan N.S. and Churchman G.J. (2017). Influence of physico-chemical properties of soil clay fractions on the retention of dissolved organic carbon. *Environmental Geochemistry and Health*, **39**, 1335-1350.

Stevenson, F.J. (1994).*Humus Chemistry: Genesis, Composition, Reactions*. John Wiley & Sons, USA.

Sulistyono, N.B., Rohman H.F., Sukri M.Z., Bintoro M., Rohman F. (2025). Effect of humic acid and blotong application on vegetative growth of chili (*Capsicum annum* L.) plant. *IOP Conference Series: Earth and Environmental Science*, **1446(1)**, 012040.

Sun, C., Bei K., Liu Y. and Pan Z. (2022). Humic acid improves greenhouse tomato quality and bacterial richness in rhizosphere soil. *ACS Omega*, **7(34)**, 29823-29831.

Taha, S.S. and Osman A.S. (2018). Influence of potassium humate on biochemical and agronomic attributes of bean plants grown on saline soil. *The Journal of Horticultural Science and Biotechnology*, **93**, 545-554.

Tavares, O.C., Santos L.A., de Araújo O.J., Bucher C.P., García A.C., Arruda L.N., de Souza S.R. and Fernandes M.S. (2019). Humic acid as a biotechnological alternative to increase N-NO_3^- or N-NH_4^+ uptake in rice plants. *Biocatalysis and Agricultural Biotechnology*, **20**, 101226.

Tei, F., De Neve S., de Haan J. and Kristensen H.L. (2020). Nitrogen management of vegetable crops. *Agricultural Water Management*, **240**, 106316.

Turhan, A., Asik B.B. and Kusçu H. (2020). The influence of irrigation water salinity and humic acid on nutrient contents of onion (*Allium* cepa L.). *Journal of Agricultural Sciences*, **26**, 147-153.

Van, T.T. and Di H.B. (2022). The effect of humic and salicylic acid on improving salt tolerance of yellow hot chili (*Capsicum annuum* L.). *JERAMI Indonesian Journal of Crop Science*, **4(2)**, 52-57.

Wei, S., Wu M., Li G., Liu M., Jiang C. and Li Z, (2018), Fungistatic activity of multiorigin humic acids in relation to their chemical structure. *Journal of Agricultural and Food Chemistry*, **66(28)**, 7514-7521.

Wen, J., Tang X., Wang M., Mu L., Hao W., Weng J., Gao Z. and Hu X. (2024). Regulation and mechanism of pyrite and humic acid on the toxicity of arsenate in lettuce. *Science of the Total Environment*, **912**, 168980.

Widari, D.N. (2024). The effect of humic acid dosage on the growth and yield of bitter melon plants (*Momordica charantia* L.). *International Journal of Multidisciplinary Research and Literature*, **3(3)**, 320-328.

Wu, S., Li R., Peng S., Liu Q. and Zhu X. (2017). Effect of humic acid on transformation of soil heavy metals. *IOP Conference Series: Material Science and Engineering*, **207**, 012089.

Yang, F., Tang C. and Antonietti M. (2021). Natural and artificial humic substances to manage minerals, ions, water, and soil microorganisms. *Chemical Society Reviews*, **50(10)**, 6221-6239.

Yaquby, A.M., Rabbani B. and Saddad S. (2024). Effect of humic acid and ascorbic acid on seed germination and growth of cucumber (*Cucumis sativus* L.) under salinity stress. *Basrah Journal of Agricultural Sciences*, **37(1)**, 105-118.

Zamljen, T., Veberiè R. and Slatnar A. (2025). Fertilization with humic acids in production changes the quality of fresh and stored sweet pepper fruits (*Capsicum annuum* L.). *Journal of Plant Growth Regulation*, **19**, 1-9.

Zandonadi, D.B., Santos M.P., Medici L.O. and Silva J. (2014). Action of organic matter and its fractions on vegetables physiology. *Horticultura Brasileira*, **32(1)**, 14-20.

Zhu, L., Liu H., Zhang Y., Cao Y., Hu Y., Wang Y., Zheng H. and Liu M. (2024). Humic acid alleviates low-temperature stress by regulating nitrogen metabolism and proline synthesis in melon (*Cucumismelo* L.) seedlings. *Horticulturae*, **11(1)**, 16.

Zohaib, M., Ahraf K., Fatima K., Komal N., Arshad A. and uz Zaman Q. (2024). Humic acid supplementation improves salt tolerance in chili by modulating morpho-physio-biochemical variables. *International Journal of Applied and Experimental Biology*, **3(2)**, 253-264.