Journal of the Saudi Society of Agricultural Sciences 22 (2023) 493–513

HOSTED BY

Contents lists available at ScienceDirect

Journal of the Saudi Society of Agricultural Sciences

journal homepage: www.sciencedirect.com

Review article

Humic foliar application as sustainable technology for improving the growth, yield, and abiotic stress protection of agricultural crops. A review

Octávio Vioratti Telles de Moura, Ricardo Luiz Louro Berbara, Danielle França de Oliveira Torchia, Hellen Fernanda Oliveira Da Silva, Tadeu Augusto van Tol de Castro, Orlando Carlos Huertas Tavares, Natália Fernandes Rodrigues, Everaldo Zonta, Leandro Azevedo Santos, Andrés Calderín García *

Laboratory of Soil Biological Chemistry, Department of Soils, Federal Rural University of Rio de Janeiro (UFRRJ), Seropédica, RJ, Brazil

ARTICLE INFO

Article history:
Received 31 December 2022
Revised 13 March 2023
Accepted 2 May 2023
Available online 10 May 2023

Keywords:
Humic substances
Biostimulants
Biofertilizers
Phytotechnics
Humic acids

ABSTRACT

The application of humic substances (HSs) promotes bioactive effects in plants, stimulating growth and development, promoting against biotic and abiotic stresses and increasing agricultural productivity. There are countless examples of fertilizers and biostimulants made from HSs that are capable of being used to form state-of-the-art intelligent agricultural technologies with increased efficiency due to their versatility and structural richness. In recent years, the phytotechnics associated with HS application to foliage have improved, and the applications have been expanded to all plant groups; however, the studies are disaggregated and still scarce, hindering the integration of data and the implementation of this technology for researchers, technicians, and specialists. The objective of this review was to gather all possible evidence related to the ability of HSs to stimulate plant metabolism when applied to foliage. This review first addressed the characteristics of foliar application and HSs. Subsequently, studies were organized by plant groups: vegetables, grasses, legumes, fruit, oilseeds, and medicinal and ornamental plants. Regardless of the plant group, HS foliar application stimulated parameters such as biomass and plant height and increased levels of photosynthetic pigments and agricultural productivity. Foliar application promoted protection against stress events, increasing the activity of peroxidase (POX), catalase (CAT), and phenyl alanine ammonium lyase (PAL) enzymes. Fruit quality also improved with HS foliar application, especially the total sugar content and the amount of oil, protein, and fiber, among others. Based on this review, we propose studies that integrate new forms and technologies of HS foliar application to plants. Experiments with various sources of origin, plant types, and environments are necessary to standardize the application forms of these compounds. Thus, we conclude that HSs are a viable technology that is environmentally friendly and highly accessible to small farmers and family farmers.

Contents

---

* Corresponding author at: Federal Rural University of Rio de Janeiro.
E-mail address: cg.andres@gmail.com (A. Calderín García).

https://doi.org/10.1016/j.jssas.2023.05.001

1. Introduction

The eradication of hunger, food insecurity, and all forms of malnutrition is one of humanity's greatest challenges. It is estimated that in 2020, between 720 and 811 million people went hungry in the world and that more than 2 billion individuals did not have access to adequate food; both values indicate significant increases compared to those in previous surveys, and this situation is exacerbated by the increase in the world's population up to eight billion people in 2022(FAO, 2022). Thus, it is essential to adopt modern agricultural practices capable of meeting this demand for food, using more sustainable approaches that reduce soil degradation and water contamination (Cristofano et al., 2021; Lipper et al., 2014). Plants biostimulants such as amino acids and humic acids are among the most effective approaches in this regard (Souri and Hatamian, 2019; Amiri Forotaghe et al., 2022; Najarian et al., 2022).

Humic substances (HSs) are materials derived from the decomposition of plant, animal, and microbial residues and from the metabolic activity of soil microorganisms, corresponding to approximately 80% of soil organic matter (SOM), and they are also found in aquatic environments and the atmosphere (Amador et al., 2018). These compounds are known to have biostimulant properties and are used by farmers to reduce the use of agrochemicals and more efficiently use nutrients to achieve more sustainable food production (Monda et al., 2021). This is mainly because they can interact with plants in a positive or negative way, stimulating or inhibiting plant development, which is also referred to as HS bioactivity. These substances beneficially affect the life cycle of plants through their role in root and leaf development, increased nutrient absorption, and the regulation of enzymes fundamental to plant metabolism. Notably, the bioactive potential of HSs depends on factors such as the species receiving the HSs, the organ treated with HSs, plant age, HS recommended dose, the source of organic material from which the HSs were extracted, and the specific physicochemical characteristics of the HSs (Zandonadi et al., 2014).

The stimulating action of HSs is well recognized in the scientific literature. The bioactivity that HSs exerts on plants is highly dependent on the HS structural characteristics and initially occurs through chemical-physical interactions with the plant root system (Asli and Neumann 2010). Such HS-root interactions promote pore clogging and modify their functioning, creating a perception of mild stress called "eustress" in plants. Under this physiological condition, plants regulate the levels of reactive oxygen species (ROS) through the synthesis of redox enzymes. This mechanism of action promotes root growth in plants and protects against stress (García et al., 2016; Castro et al., 2021, 2022). Studies conducted by de Hita et al. (2020) showed that the beneficial effects of HSs when applied to both foliar and root tissues were due to adaptation to mild stress that is regulated mainly by the action of jasmonic acid.

Thus, the effect of HSs on plants when applied via foliar application has been established. Foliar application is a fertilization method widely used as an alternative to soil application of fertilizer, thus contributing to more environmentally sustainable agriculture. This practice has been used to apply macro- and micronutrients, as well as biostimulants and humic fertilizers, favoring the assimilation and use of nutrients by plants and increasing crop yield and quality (Manuel-Tejada et al., 2018). The use of HS-enriched compost extracts is an economically important tool for foliar spraying, especially when soil nutrient absorption is impaired, such as under calcareous conditions due to nutrient precipitation. However, this type of fertilization is limited to certain climatic conditions since high temperatures, rainfall, and wind reduce its efficiency. Similarly, high application rates can damage plants, such as through leaf burns due to the concentration of salts after water evaporates (Jindo et al., 2020).

HSs have the ability to protect plants against abiotic and biotic stresses, as well as stimulate their growth and development, promoting increases in yields and agricultural production (Perminova et al., 2019). HS use in fertilizers and plant biostimulants has grown in recent years and is part of the phytotechnics and current management of various crops in various parts of the world (Olk et al., 2018). Despite this scenario, there is still a need to understand the modes of action and the regulation mechanisms that govern plant actions when HSs and HS-based fertilizers are applied via foliar application. Most current studies are incomplete and still insufficient, which hinders the advancement of research and the understanding of specialists and technicians in the fields and areas in question. Thus, the present review aims to identify and consolidate the main results obtained in these studies of HS foliar application in the most diverse crops of economic interest, either in field experiments or in greenhouses. For this study, species were separated into the following groups: vegetables, grasses, legumes, fruits, oilseeds, and medicinal and ornamental plants. Thus, a general evaluation of the ability of HS to improve plant development and growth through foliar spray was conducted, and based on the level of stress protection from HS, ideal doses and application times were determined.

2. Foliar fertilization

The ability of plants to absorb water from the environment through their leaves has been known for approximately three hundred years. However, nutrient absorption and its physiological effects were only demonstrated in the 19th century, such as through the pioneering work of Gray in 1843, who evaluated the foliar application of nutrient solution as an alternative fertilization of grapevines (Fernández et al., 2013). In parallel with these studies, there was also progress in understanding the surface structure of leaves (Brongniart 1834; von Dohl 1947). During the second half of the 19th century, studies on gas exchange, transpiration, leaf anatomy, and physiology were published (Boussingault 1868; Merget 1873; Sachs 1884, van Wissenlingh 1895). In the 20th century, researchers used techniques with radioactive isotopes combined with electron microscopy to help establish the basis for foliar fertilization (Mocellin 2004; Fernandez and Eichert 2009).

The foliar fertilization technique consists of supplying nutrients directly to the leaves by spraying a solution containing one or more nutritive elements essential for plant development that must be distributed to the other parts of the plant (Mocellin 2004; Fernández et al., 2013). This method is considered fast and efficient in overcoming plant malnutrition, as it supplies plants with nutrients more readily compared to soil application (uptake via the root) (Fageria et al., 2009). However, foliar fertilization should not completely replace soil fertilization but should be a complementary technique to be performed in critical periods of high plant demand or when soil nutrients are not available (Nachtiqaü and Nava 2010).

One of the factors that influences the performance of foliar fertilization is the characteristics of the plant itself, especially the leaves. Leaf surfaces are usually covered by cuticles, which are covering tissues composed of hydrophobic biopolymers that block moisture loss (Kritzinger and Lötze 2019). The cuticles may have embedded waxes (intracuticular) or deposits on their surfaces (epicuticular), and their main polymers are cutin and cutaneous, which are found in varying proportions depending on the plant species (Jeffree 2007). Due to these components, the cuticle has a complex network of interesterified fatty acids (C_{16} and/or C_{18}), in addition to n-alcohols (C_{20}-C_{40}), n-aldehydes, and n-alkanes (constituents of waxes) (Fernández et al., 2013).

Because of this hydrophobic characteristic of leaf surfaces, cuticular permeability is required for nutrient solution flow. In addition, cuticles are generally composed of three layers: the outermost layer, where epicuticular waxes predominate; the matrix layer of biopolymers (cutin and/or cutaneous) and intracuticular waxes; and the innermost layer, containing, in addition to the aforementioned biopolymers, polysaccharides from the cell walls of epidermal cells. The middle lamellae and pectin layers are found just below this innermost cuticular layer so that some amount of polysaccharide fibrils and pectin lamellae extend from the cell wall, connecting this underlying tissue with the cuticle (Fernández et al., 2013). Thus, there is a gradual increase in the negative charges of the epicuticular wax toward the pectin layer, which creates an electrochemical gradient and may cause the movement of cations and water molecules (Franke 1967). There is an area of study that considers the possible presence of "aqueous pores" arising from the absorption of water molecules by polar units of the cuticle, which would explain the penetration of hydrophilic solutes. However, no evidence has been found to support this theory (Fernández et al., 2013).

There are different structures on plant surfaces (stomata, trichomes, and lenticels) that can also absorb nutrient solutions and other chemicals. Stomata are small, specialized pores consisting of two guard cells, whose opening and closing dynamics control gas exchange between the leaf and the atmosphere (Gerardin et al., 2018; Huang et al., 2020). Trichomes are unicellular or multicellular appendages that protrude from the epidermis (Bustamante-Eguiguren et al., 2020) and may facilitate the absorption of nutrients due to their low cutinization (Tagliavini and Toselli 2005). Lenticels are macroscopic epidermal structures that can be found on stems, pedicels, or fruits and can also absorb solutions applied to the aerial parts of plants (Fernández et al., 2013).

Evaluating the possible absorption via stomata of aqueous solutions, (Burkhardt et al., 2012) confirmed the occurrence of this process, as the abaxial (stomatal) surface of apple leaves absorbed more than the adaxial (nonstomatal) surface. In the same sense, (Schreel and Steppe 2020), a review on foliar water uptake by several groups of plants highlighted the fundamental role of stomata in allowing the entry of water and other solutes into plant cells. The two studies cited above also emphasize the influence that aerosol particles (for example, hygroscopic salts) naturally deposited on leaf surfaces exert on leaf wetting and water absorption. These substances, when undergoing repeated cycles of deliquescence (absorption of moisture from the air until it forms a solution) and efflorescence (loss of water to the atmosphere), can cause the development of thin water films on the hydrophobic surface of leaves. Such hygroscopic particles are able to change the cuticular hydrophobicity and water surface tension, allowing increased wetting of the leaf surface and favoring the absorption of water and nutrients. (Burkhardt et al., 2012).

In addition to the natural deposition of hygroscopic substances on leaf surfaces, wetting and absorption of nutrient solutions into these aerial organs can also be boosted by the addition of coformulants in the fertilizer solution being applied, which are also known as adjuvants. There are several types of these products that are categorized according to their mode of action: surfactants (reduce surface tension), adhesives (increase solution retention, ensuring greater resistance to rain), penetrants (increase the rate of foliar penetration, "solubilizing" cuticles), humectants (slow down the drying of the solution by lowering the deliquescence point of the formulation on the leaf), among others (Fernández et al., 2013). Rodrigues et al. (2020) evaluated the foliar application of lanthanum (La) and cerium (Ce) nitrates in soybean and found that the addition of the 0.01% surfactant Triton HW 1000 reduced the droplet contact angle on both sides of the leaves, increasing wettability. Due to this increased efficacy in the wetting of leaf surfaces and the absorption of fertilizers by the plants, the adjuvants also contributed to reducing negative environmental impacts given the use of smaller amounts of active ingredients in the formulations and given the fact that most of the applied product is actually used by plants (Kovalchuk and Simmons 2021).

Despite the advantages of foliar fertilization, it is difficult to predict the responses of plants since the effectiveness of this procedure depends on several factors, such as the plant species in question, leaf cuticle composition, application time, phenological aspects, and environmental conditions (Portu et al., 2015). According to Fageria et al. (2009), for foliar uptake to be efficient, it is essential that the stomata are open and that the temperature is not too high to avoid damage such as leaf burns. Similarly, these authors recommend that applications should not be performed on windy and rainy days until 4 h after spraying, which would affect foliage wetness. del Amor and Cuadra-Crespo (2011) worked with pepper plants (*Capsicum annuum* L., cv. Herminio) and highlighted the influence of temperature on the antioxidant response of the plant after foliar application of urea. The timing of spraying may also be a determining factor in the success of this fertilization technique. Analyzing the foliar application of manganese (Mn) to cucumber (*Cucumis sativus* L.) to increase resistance against powdery mildew (fungal disease caused by the fungus *Podosphaera fuliginea*), Eskandari and Sharifnabi (2020) found that the shortest interval between nutrient spraying and pathogen inoculation resulted in maximum fertilization efficacy. Portu et al. (2015) studied the production of phenolic compounds in grapes after foliar fertilization with urea and emphasized that the plant responses were related to the application time since the accumulation of such compounds intensified after maturation, when vegetative growth is slower, favoring this greater reserve of secondary metabolites.

Frioni et al. (2021) evaluated the influence of *Ascophyllum nodosum*, a brown alga, extract on vines subjected to progressive water stress, comparing two application methods: foliar and soil. These authors found that the two forms of treatment had contrasting results, with foliar spraying being more effective than soil application, preserving the integrity of the photosynthetic apparatus and more quickly restoring the physiological function of the leaf during the rehydration period. Similarly, Zhou et al. (2021) studied the effect of foliar and soil applications of selenium (Se) and silicon (Si) to reduce cadmium (Cd) toxicity in wheat varieties (*Triticum turgidum* L.). Soil application of Si and Se was effective in controlling Cd concentrations in both varieties, while the foliar method was successful for only one variety. These results were due to the regulation of Cd transporter genes and improvement in the activity of antioxidant enzymes. On the other hand, Boldrin et al. (2013) concluded that soil Se application was more effective than foliar application in increasing Se concentrations in rice grains.

Another way of performing foliar fertilization of crops is using HSs, which are structurally irregular organic materials widely present in soils, rivers, oceans, and sediments, in addition to natural resources related to coal (peat, leonardite, and lignite) (Jung et al., 2021). Such substances are compounds formed by the chemical and biological transformation of animal and plant residues through the action of soil microorganisms and have the ability to promote plant growth and the assimilation of the main nutrients required by plants, such as nitrogen (N), phosphorus (P), and potassium (K) (Leite et al., 2020). However, due to their great structural complexity, the nature of HSs still unclear, so the relationship between their beneficial effects on plants and their molecular structure has been the subject of many studies that have even produced contrasting results (Pizzeghello et al., 2020). Thus, the main forms of action of HSs on plant development are discussed next, and the results of studies that evaluated its foliar application to different crops will be presented (Fig. 1).

3. Humic substances and their action in plants

HSs consist of complex mixtures of heterogeneous organic materials naturally present in soils, waters, and sediments (Stevenson 1994) that have been extensively transformed since their production, for example, by plants (Tranvik 2014). Operationally, they can be separated and classified into the following fractions: fulvic acids (FAs, soluble in acid and alkaline pH), humic acids (HAs, insoluble at acid pH and soluble at alkaline pH), and humin (insoluble at acid and alkaline pH) (Stevenson 1994).

HSs are formed through a process known as humification, a heterogeneous and complex process, where chemical, biochemical, and enzymatic transformation reactions occur in soils and in natural systems, decomposing and creating conditions for the formation of new chemical structures with greater stability than their precursors. The humification process depends on the chemical and structural characteristics of the molecules incorporated into the soil and the extent to which this process occurs. The humification rate is regulated by environmental conditions, that is, soil moisture, mineralogical composition, and the quantity and diversity of soil biota. Humification will therefore produce the specific HSs in each environment where they are formed. Thus, a HS has a single structural nucleus with a supramolecular organizational level, specific and common to this group of compounds but with varying relative amounts of structures in its composition (Aguiar et al., 2022).

The supramolecular structural model applied to HSs seems to better explain the chemical properties and functions of HSs in the environment. In the supramolecular structural model, HSs are composed of small heterogeneous molecules that are arranged in structures of larger molecules and are united by weak intermolecular interactions, van de Waal interactions, hydrophobic interactions (π -π, CH-π) and hydrogen bonds (Piccolo 2002, Nebbioso et al., 2014). The structure of HSs in a supramolecular organization is considered stable in the soil, where these compounds are organized themselves with a surface domain formed by polar, hydrophilic structures, involving a domain disposed toward the interior of the structure with aromatic and hydrophobic characteristics (Fischer 2017). Computational chemical modeling has already shown that the formation of supramolecular structures occurs in the soil and begins with an absorption at the reactive surfaces of the soil mineral fraction of smaller molecules or partial molecular subaggregates that serve as the basis for the formation of larger multimolecular aggregates (Gerzabek et al., 2022) (Fig. 2).

HSs have the ability to improve the nutritional status of plants in different ways: increased expression of gene isoforms that encode for plasma membrane proton pumps (PM H^+ -ATPase) of roots and increase their activity (Tavares et al., 2017; Zandonadi et al., 2007); promotion of ion transport to plant tissues; regulation of the expression of genes that encode the main nutrient transporters in the roots; and increased activity of enzymes that affect

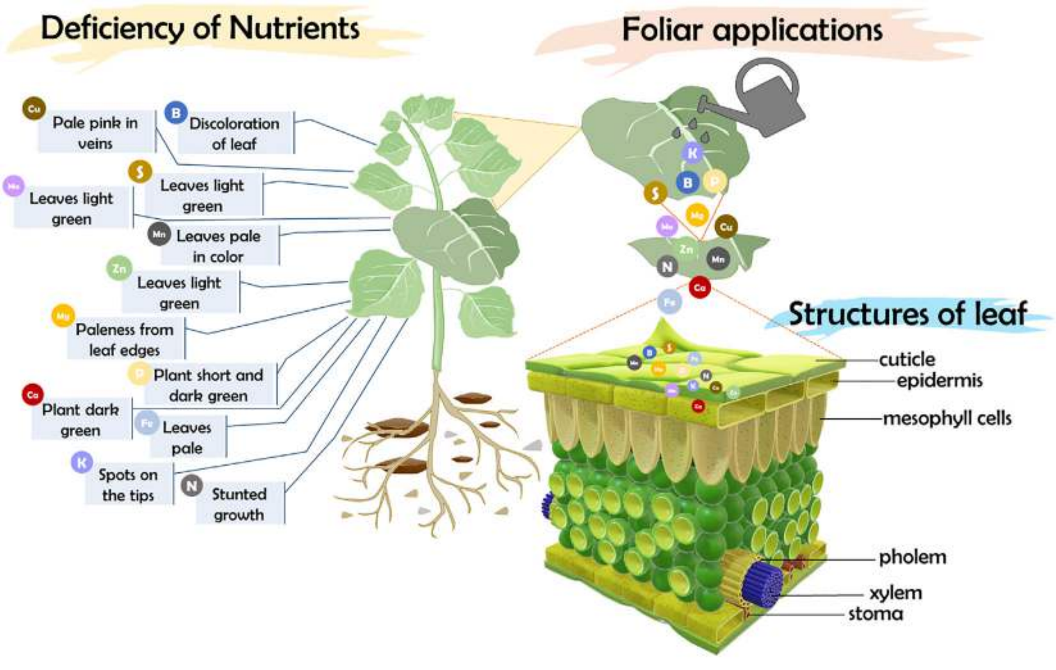

Fig. 1. Leaf structure, showing the cuticles covering hydrophobic tissues. Extracted from Fernández et al. (2013).

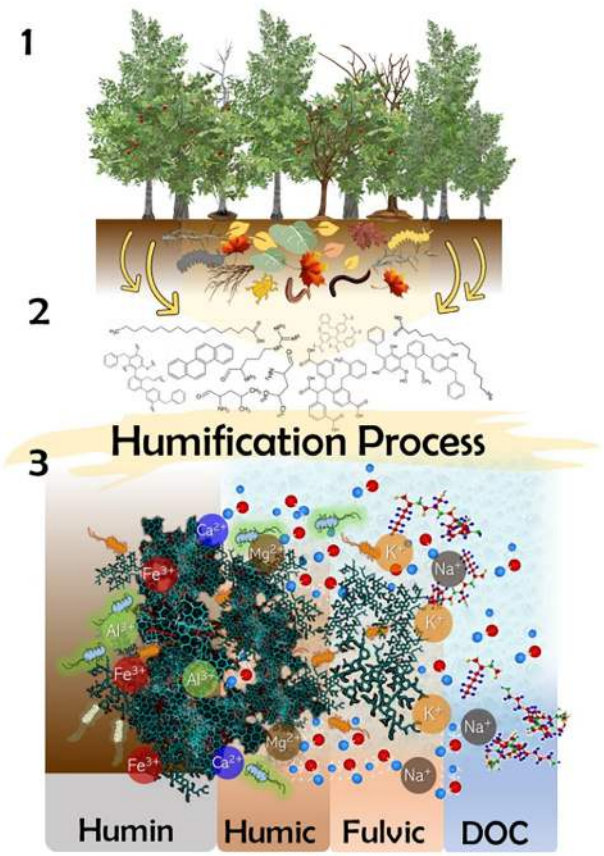

Fig. 2. Illustrative scheme that shows the formation of supramolecular humic structures from the deposition of organic matter in the soil. 1) Deposition of plant and animal debris in the soil. 2) Incorporation of organic molecules into the soil, decomposition products, and 3) formation of humic fractions and dissolved organic carbon (Aguiar et al. 2022).

the use of nutrients (e.g., nitrate reductase, glutamine synthetase, glutamate synthase, and phosphoenolpyruvate carboxylase - PEP-case,)(Urrutia et al., 2020). Therefore, HSs act on nitrogen assimilation and carbon metabolism, in addition to the synthesis of secondary metabolites, such as phenylpropanoids (Zanin et al., 2019).Vaccaro et al. (2015) found a positive effect of low HS doses on the activities of the main enzymes involved in the reduction and assimilation of inorganic nitrogen in maize seedlings, while Leventoglu and Erdal (2014) found no positive effects of high HS rates on plant growth and nutrient concentrations in maize grown in highly calcareous soils. In turn, Akladious and Mohamed (2018) found that the highest dose of HA (1500 mg. kg^{-1} of soil) was more effective than the lowest dose (750 mg. kg^{-1} of soil) in increasing the levels of nitrogen, phosphorus, and potassium in pepper plants (*Capsicum anuum* L.) subjected to salt stress. These authors also observed the influence of HS on the contents of antioxidants and secondary metabolites, as evidenced by increases in the levels of anthocyanin, ascorbic acid, and total flavonoids in the shoots of pepper plants.

Due to all the influence of HS on the promotion of plant growth, whether they exert possible hormonal activity is a question. Over the last decades, several studies have demonstrated this other potential HS action in stimulating plant development (O'Donnell 1972; Albuzio et al., 1989; Nardi et al., 1994; Varanini and Pinton 1995; Muscolo et al., 2013; Nardi et al., 2021). There is evidence that HSs can be considered an environmental source of indole acetic acid (IAA), a type of auxin, which is the most studied class of phytohormones acting in cell division and expansion (Zandonadi et al., 2010). It is believed that HSs can behave as an exogenous auxin, regulating root growth and morphology. This is because these humified materials enclose IAA and other molecules with IAA-like activity, which may be of microbial or plant origin in the soil (Nardi et al., 2021). In addition to auxins, activities related to other phytohormones, such as cytokinin and gibberellin, have been observed in HSs. Pizzeghello et al. (2013) found for the first time the presence of isopentenyladenosine (IPA), a cytokinin, at physiologically active concentrations in humic materials from different sources, while authors such as Nardi et al. (2000a, 2000b) and Pizzeghello et al. (2002) reported gibberellin-like activities in HSs. According to Nardi et al. (2018), this hormonal action observed in HSs reasonable since soils have variable auxin contents, which are higher in more fertile soils. In addition, these authors also stated that the levels of auxin and gibberellin are, as a rule, higher in the rhizosphere region, possibly due to the increase in microbial populations and metabolism due to the presence of root exudates. Finally, the authors emphasized that the observed hormonal effects did not necessarily correlate with the auxin levels identified in the HSs, thus fueling the debate about the possible presence of different auxin family compounds or humic structure molecules that mimic the action or stimulate the endogenous metabolism of this phytohormone in plants.

Another relevant point in studies on the effects of HSs on plant growth was the protective action that these substances confer to plants against various types of stress. Many studies have been published identifying the importance of HS in acting against stresses caused by heavy metals (Pittarello et al., 2018; Duan et al., 2020; Haider et al., 2021), salinity (Hatami et al., 2018; Saidimoradi et al., 2019), drought (Khorasaninejad et al., 2018; Qiu et al., 2021), and high temperatures (Cha et al., 2020; Khan et al., 2020). Yildirim et al. (2021) found that the application of a formulation containing HA and FA was effective in mitigating the negative impacts caused by cadmium (Cd) accumulation in garden cress (*Lepidium sativum* L.).

These authors found that treatment with HSs increased the fresh and dry mass of roots and shoots, the stem diameter, the leaf area, and the nutrient contents and reduced the activities of the antioxidant enzymes catalase (CAT) and superoxide dismutase (SOD) and increased the activities of the enzyme peroxidase (POD). HSs contribute to plant development under stress conditions by improving photosynthesis, respiration, cell membrane permeability, and absorption of nutrients such as phosphorus and potassium, in addition to ensuring a hormonal balance (Kaya et al., 2020). The application of these humified compounds under stress can also trigger an antioxidant response. Stress from metals, such as Cd, increases the generation of ROS, such as hydrogen peroxide (H_2O_2) and superoxide anion ($O_2^{\cdot -}$) (Ozfidan-Konakci et al., 2018).

Despite the toxicity caused by ROS, these chemical species also have the potential to act as signaling and regulatory molecules. During abiotic stresses, the ROS produced signal changes and regulate gene expression (Demidchik et al., 2007). The action of the negative or positive effects of ROS depends on the homeostasis balance between the production and elimination of ROS that may alter the regulatory role of these signaling substances, favoring negative effects (Monda et al., 2021). According to García et al. (2019), the interactions between humic fragments and plant roots cause changes in redox homeostasis, which regulates ROS levels and mediates the action of HSs in plants, especially mechanisms associated with root growth and development. This interaction of HSs with the roots causes agglomeration on the root surface, leading to the expression of antioxidant enzymes such as CAT and increasing the levels of ROS, which act as intermediates in plant growth (García et al., 2012). Thus, when applied to the soil or plants as biostimulants, HSs can act as eustressors, which are stress factors that trigger a mild and transient stress level in plants, resulting in improvements in metabolism and vegetable production (Castro et al., 2021). Hydrogen peroxide (H_2O_2) is a ROS that is quite stable in plants and diffuses through membranes so that small concentrations of H_2O_2 can result in the adaptation of plants to various types of stresses, and this process can occur through its role as a signaling molecule (García et al., 2012). Working with the application of HAs from different origins in rice plants (*Oryza sativa* L.), Castro et al. (2021) observed that initially (96 h), treatment with humic material reduced the photosynthetic performance of the plants. However, after 144 h of application, there was an increase in photosynthesis, and after 192 h, photosynthetic activity was re-established, resulting in changes in nitrogen metabolism and plant development, indicating that there was a state of eustress after HS application.

The action of HSs in plants is directly related to the HS structure (Fig. 3). Studies performed with 37 fractions of humified organic matter showed that when applied to rice plants via the roots, the C-aliphatic, substituted C-aromatic, and C-carboxylic structures in HSs are responsible for root growth, while in HAs, the C-aliphatic, unsubstituted C-aromatic, and C-carboxyl structures account for the bioactivity in plants (García et al., 2016). As previously noted, HSs are able to stimulate plant growth through eustress, a type of mild, beneficial stress that promotes biomass increase, improves plant nutrition, and protects against abiotic stress. (García et al. 2019). HS-type compounds obtained from lignin residues showed that the structures responsible for bioactivity in maize plants are C-methoxyl and C-aromatic (Savy et al., 2020).

In Monda et al. (2018), more hydrophobic humic materials were active at low concentrations than at high concentrations, favoring their adhesion to the root surfaces of maize (*Zea mays* L.), and those with a higher content of phenolic compounds (potential inhibitors of nitrogen absorption) exerted this bioactivity at higher concentrations, forming larger and conformationally more stable supramolecular aggregates and preventing the release of these toxic molecules. In a recent review of the relationship between the structural composition and bioactivity of HSs, Nardi et al. (2021) stated that these effects of plant growth promotion depend on factors such as HS origin, dosage, degree of hydrophobicity and aromaticity, and molecular size and the spatial distribution of the hydrophobic and hydrophilic domains. The authors highlighted that HSs with smaller molecular sizes are able to enter root cells and directly trigger intracellular signals, while those with larger molecular sizes can bind to external cellular receptors to induce molecular responses.

4. Foliar application of HSs to plants

HSs have been shown to have beneficial effects on various plant groups, such as vegetables, grasses, legumes, fruit, oilseeds, and medicinal and ornamental plants. The effects are diverse and include changes at the biochemical, morphological, and stress-protection levels (Table 1). Due to all the effects of HSs in promoting plant growth previously reported, these substances are widely used as biostimulants for several crops of agronomic interest. Although most studies address the application of these humic materials to plant roots, another way of supplying HSs is through its direct application to leaves (Olaetxea et al., 2018). Unlike the effects of HSs on roots (H^+-ATPase activation, ion transport in the plasma membrane, hormonal responses, among others), the effects on leaves have been minimally explored, and there are reports that foliar application of humified compounds increases chlorophyll levels and acts on photosynthesis. In addition, foliar application also influences transpiration, although the mechanisms are still uncertain, with increases and decreases in water loss and gas exchange in leaves (Rose et al., 2014).

The studies performed by Olaetxea et al. (2018) highlighted that the positive effects of HS application to leaves are probably regulated by mechanisms different from those triggered by HS application to the roots. These authors also emphasized that it is possible that HS treatment via leaves under field conditions also generates some effect on the soil because part of the applied solution does not reach the leaves or there is eventual HS runoff after application to the leaves. However, in cultures with large leaf surfaces and high plant density, this fact becomes negligible. Furthermore, foliar spraying of HSs alone can stimulate the development of both roots and shoots of treated plants, and this method has the potential to be more economical than soil application because the quantities of product demanded are relatively low (Chen and Aviad 1990). Kishor et al. (2021) found that in comparison to the control treatment with only NPK fertilizer, the combined application of HA to leaves and the soil, plus 100% of a recommended dose of fertilizer (NPK) in three plots plus the foliar spraying of a nutrient mixture, was the most efficient treatment and had the highest economic return in coffee plants, increasing their yield, as well as the nutrient contents in the leaves.

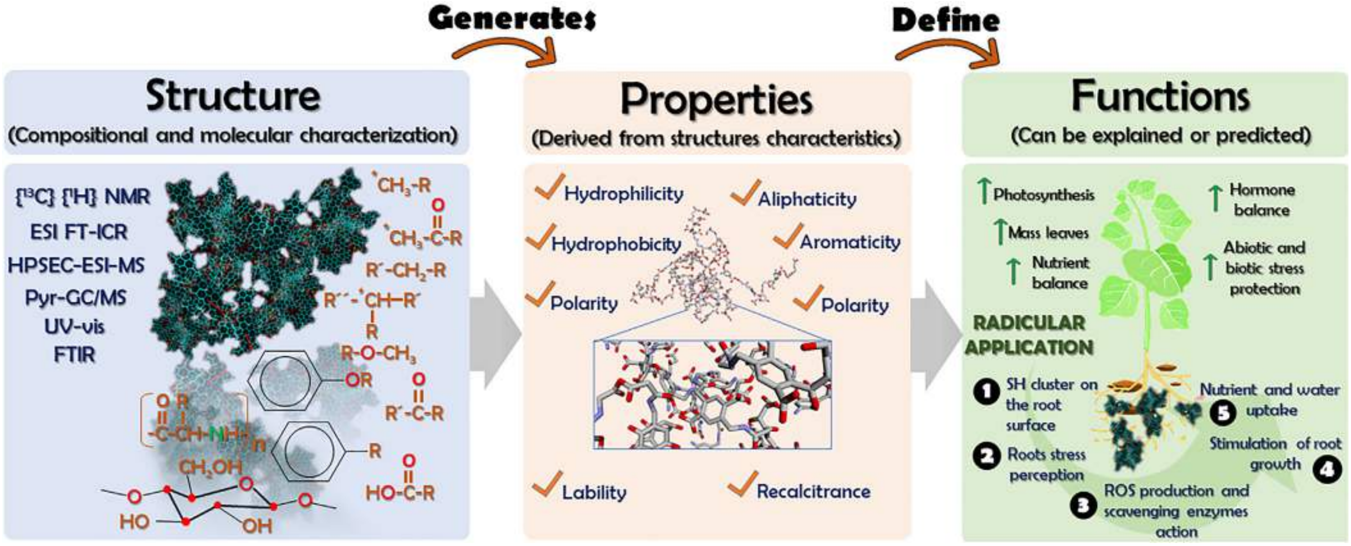

Fig. 3. Structure-property-function relationship of the effect of HSs on plants.

Table 1
Main increases observed after foliar application of humic substances in cultures of different groups (% TSS = percentage of total soluble solids).

Group of Plants	Variables with Observed Increases	Species	References
Fruits	Plant height, Number of leaves, Average fruit weight, Number of fruits % OSH, Yield	Tomato, Pepper, Cucumber, Eggplant	de Hita et al., 2020; Azarpour, 2012; Karakurt et al., 2009; Olivares et al., 2015
Leafy vegetables	Plant height, Stem diameter, Head width, % Nutrients in the leaf	Lettuce, Broccoli, Cauliflower	Rachid et al., 2020; Raheem et al., 2018
Tuber vegetables	Bulb weight, Teeth pungency, Number of leaves, Tuber yield	Garlic, Onion, Potato	Balmori et al., 2019; Kandil et al., 2012; Man-hong et al., 2020
Grasses	Number of tillers, Root surface, Harvest index, Grain yield	Rice, Corn, Sorghum Wheat	Anjum et al., 2011; Delfine et al., 2005; Felipe et al., 1998; Osman et al., 2013
Legumes	Plant height, Number of pods, Seed weight, Yield	Beans, Peas, Soybeans	Basha et al., 2020; Kaya et al., 2005; Lenssen et al., 2019
Fruit trees	Plant height, Stem diameter, Chlorophyll content in leaves, Fruit yield	Grape, Guava, Mango Passion fruit	Abdulhameed Ibrahim and Abdulali Al-Sereh, 2019; Cavalcante et al., 2013; El-Hoseiny et al., 2020; Ferrara and Brunetti, 2010
Medicinal oilseeds	Plant height, Leaf area, Photosynthetic efficiency, % Oil in seeds	Sunflower, Rapeseed, Mint Sesame,	Deotale et al., 2019; Lotfi et al., 2015; Shahabivand et al., 2018; Shindhe et al., 2020
Ornamental	Number of flowers, Flower diameter, Flowering duration, Pot life	Calendula, Chrysanthemum, Gladiolus, Petunia	Ahmad et al., 2013; Boogar1 et al., 2014; Hasan, 2019; Mazhar et al., 2012ª

Similarly, De Hita et al. (2020) explored the distinction between the effects of sedimentary HA application to the leaves and to the roots of cucumber plants (*Cucumis sativus* L. var. Ashley). The authors found important similarities and differences between the two methods of HA delivery. Both forms of application promoted the growth of both the shoots and the roots, with increases in the concentrations of IAA in the roots and of cytokinins in the shoots. It was also found that short-term foliar spraying reduced the number of secondary roots (unlike root application) and increased the length and dry mass of taproots. The researchers explained these results based on the root concentration of two phytohormones involved in the regulation of root growth: IAA and abscisic acid (ABA). While root application increased IAA and ABA levels, foliar spraying only increased IAA levels. Although the ABA root contents decreased with the HA foliar supply, this fact did not affect root growth, as verified by the higher dry matter production, in contrast to the results of Olaetxea et al. (2019), where the application of an ABA biosynthesis inhibitor impaired the root development of this same cucumber variety. Therefore, De Hita et al. (2020) stated that other factors must be involved in the observed effects of HA foliar application on growth and root architecture. On the other hand, this decrease in ABA levels in the roots may have been associated with the growth of the shoots after foliar spraying.

Another point highlighted by De Hita et al. (2020) is that foliar application of HA may have triggered signaling pathways, as the interaction of humic compounds with leaf surfaces does not occur naturally, which may induce plants to perceive this as a stressor, activating signaling networks such as a defense mechanism. In this case, the plants activated the salicylic acid and jasmonic acid (JA) signaling pathways. The foliar-treated plants showed an increase in the levels of JA and jasmonoyl isoleucine (JA-Ile), the active form of the hormone, in the roots and shoots, while root application of HA increased the level of this hormone only in the roots. The authors stressed that these hormonal changes are symptoms related to stress, associated with the loss of leaf trichomes and the decrease in chloroplast size, reaffirming the hypothesis that the observed beneficial effects were the result of a mild and transient stress condition caused by application of HA.

4.1. Foliar application of HS in vegetables

Vegetables are herbaceous or subwoody plants, generally intensively cultivated in short cycles, and they are usually cultivated in small vegetable gardens (Zárate and Vieira 2017). They are sources of vitamins, fiber, minerals, and other bioactive compounds, and their consumption is widely recommended for improving human health; they also play a key role in strengthening family farming (Faulin and Furquim De Azevedo 2003). This group of plants can be subdivided according to the parts used for human consumption; for example, the edible parts of tuberous or underground vegetables are located below the soil surface (potatoes, yams, onions, garlic, yams, cassava, beetroot, sweet potato, carrot, etc.); the edible parts of herbaceous or leafy vegetables develop above the soil surface, with succulence and softness characteristics (lettuce, cabbage, spinach, etc.); and the edible part of fruit plants are the green or ripe fruit (squash, tomato, cucumber, melon, watermelon, pepper, etc.) (Camargo Junior et al., 2018). Many vegetable species have a relatively low nutrient use efficiency compared to that of other crops (Tei et al., 2020). This scenario results in excess fertilization of the soil, which is then negatively affected (Zandonadi et al., 2014). Thus, more sustainable agriculture based on organic inputs, including the use of HS-based foliar fertilizers, may be a solution.

Lettuce (*Lactuca sativa* L.) is among the most studied vegetable species in relation to foliar application of HSs. Wang et al. (2019) evaluated spraying a solution containing FA at concentrations of 0, 0.1, 0.3, 0.5, 1.0, and 2.0 g. L^{-1} on lettuce plants subjected to cadmium (Cd) stress. The authors found that the FA treatment mitigated the negative effects of Cd stress in a dose-dependent manner, where the intermediate dose of 0.5 g. L^{-1} was the most effective in reducing the accumulation of this heavy metal in the roots and shoots of the plants. A significant increase in shoot and root growth; greater protection of the photosynthetic apparatus, especially photosystem two (PSII), to Cd stress; a reduction in the accumulation of ROS; and an increase in the activity of antioxidant enzymes, such as ascorbate peroxidase (APX) and CAT, were observed in this study. In addition to the use of HSs to protect plants against abiotic stresses, many other studies have found improvements in several parameters related to the development of lettuce plants. Rodrigues et al. (2018) and Santos et al. (2018) observed that the application of HA from an alternative and commercial source benefited the growth of lettuce seedlings of the cultivar Elba, and the best doses were 3.0 mg. L^{-1} (both HA sources) in the first study and 21.9 g. L^{-1} of the alternative source and 7.3 g. L^{-1} of the commercial source in the second study.

In turn, Hernandez et al. (2015) evaluated the application of potassium humate isolated from cattle manure vermicompost directly to the leaves of the lettuce cultivar Black Seed Simpson in an urban organic farming system in Cuba. The humates were applied at concentrations of 0, 10, 15, and 20 mg C. L^{-1} at 10 and

15 days after transplanting. The authors found that of the humate concentrations, 15 mg C. L^{-1} was the most efficient for increasing the number of leaves per plant, reducing carbohydrate levels, and increasing the protein content and activities of the enzymes nitrate reductase (NR) and phenylalanine ammonia lyase (PAL), with the latter being fundamental in the synthesis of phenolic compounds that act in the defense of plants against herbivores. It was also hypothesized that compounds present in the humified complex may act as inducers of PAL activity. These authors also highlighted that the application of humates directly to the leaves activated their metabolism, accelerating development by reducing the production cycle, without affecting the commercial quality of the plants, which is a possible mechanism for improving urban agriculture. In addition to lettuce, other leafy vegetables, such as broccoli (Al-Jaf et al., 2018), cauliflower (Rachid et al., 2020), and asparagus (Tejada and Gonzalez 2003), have also been the subject of studies on the foliar application of HSs, and all vegetables experienced responses related to developmental characteristics.

Of the different vegetables, tuberose or subterranean plants are another group that has been widely studied. Two recent studies on potato (*Solanum tuberosum* L.) found that foliar application of HSs increased tuber yield (Man-hong et al., 2020; Wadas and Dziugieł 2020). However, only the first study showed a significant increase in chlorophyll levels under water stress conditions in a controlled experiment in a greenhouse. The authors of the second study did not find an increase in chlorophyll contents in a field experiment on a Luvissol and reported that this parameter depends on the cultivar used and the climatic and soil conditions. In turn, Dziugieł and Wadas (2020) performed a similar experiment under the same field conditions as the aforementioned study by the same authors Wadas and Dziugieł (2020) in three successive years, where the HS leonardite (12% HA and 6% FA) was sprayed twice (first in the leaf development stage and again one week later). The results showed that there was not an increase in the number of tubers per plant but an increase in the average weight of the tubers, resulting in a higher total and marketable yield. In addition, these researchers found that HA application produced better results in the coldest growing season with periodic water shortages than in the hottest growing season during potato development, reaffirming the effect of HSs related to overcoming water stress, for example, reducing the rate of transpiration. On the other hand, Suh et al. (2014), evaluating the foliar spraying of FA plus soil application of HA in this same crop, observed that the direct treatment on the foliage did not affect the number of tubers or their total yield and chemical composition. However, in this experiment, there was an increase in the weight of extra-large tubers (greater than250 g), increasing the incidence of hollow heart disease, which led the authors to state that under the conditions evaluated, FA spraying is not recommended.

Garlic (*Allium sativum* L.) and onion (*Allium cepa* L.) belong to the same genus and are also classified as underground or tuberous vegetables. In addition, there are many reports in the literature addressing the foliar application of HS-based products to these species. Regarding garlic, there are studies showing both an increase in the levels of macro- and micronutrients, the pungency of the cloves (Manas et al., 2014), the weight of the bulbs, yield of cloves per bulb, and storability (Abdel-Razzak and El-Sharkawy 2013). Balmori et al. (2019) evaluated the effects of spraying a liquid humic extract derived from vermicompost in a field experiment 45 days after planting garlic seeds. The authors observed an increase in the external mass of garlic cloves, in addition to commercial quality parameters, and they related these responses to the structure of the applied humic material, with a predominance of aliphatic compounds such as carbohydrates, peptides, and more labile lignin fragments, which conferred the bioactivity potential of the applied HS. Regarding the onion crop, Kandil et al. (2012) showed that foliar spraying of HAs (4.76 L. ha^{-1}, twice, at 60 and 80 days after transplanting) provided the highest results for growth-related traits (plant height, number of leaves per plant, plant fresh weight). foliage and bulb proportion), as well as % total soluble solids (TSS), bulb weight, and total and marketable yield of cultivar Giza 20. These responses were attributed to the action of the HS in stimulating the initial growth of the onions, as well as in the greater production of dry matter and the synthesis of metabolic products that are translocated to the bulbs. In an opposite trend, Osvalde et al. (2013) did not find a positive influence of the foliar spraying of an HS derived from vermicompost (1.5 L. ha^{-1}, two or three times) on nutrient contents and onion yield in a field experiment in Latvia. These contrasting results can be explained by the diversity in the origin, composition, and dosage of the applied HSs, as well as by the environmental and cultivar variability studied.

Evaluating the foliar application of HSs in carrots (*Daucus carota* L.), Alhariri and Boras (2020) found a significant increase in plant growth and root yield, with higher plant height, plant, and leaf and root fresh mass, in addition to a better harvest rate. Positive effects on this culture were also found by El-Helaly (2018), where spraying HA (1 g.L^{-1}) and FA (0.5 g.L^{-1}) was tested, with both being applied four times (at 30, 45, 6,0 and 75 days after sowing) in four different cultivars. In general, in comparison to FA, HA was more efficient in increasing root weight and diameter and yield and harvest index, while FA was more efficient in increasing % dry matter, total carbohydrates, total carotenoids, nitrogen, and phosphorus in the roots, in addition to the total leaf chlorophyll content. Foliar spraying of FA (10 mg. L^{-1}) on sugar beet (*Beta vulgaris* L.) increased root weight, diameter, and length; the root/shoot ratio; and the biological yields of roots, shoots, and sugar, in addition to the percentages of sucrose, TSS, and purity (Kandil et al., 2020). In addition to these parameters, Abido and Ibrahim (2017), who applied HA (1.5 mg. L^{-1}, at 50 and 70 days after sowing), among other products, also showed higher levels of chlorophyll in the leaf, leaf area, and length, as well as higher relative and culture leaf growth rates.

Of the fruit plant group, tomato (*Solanum lycopersicum* L.) is one of the crops with more studies related to HS bioactivity. The authors Villegas-Espinoza et al. (2018) tested in a field experiment the foliar application of the product Foliar Liplant®, with 50% HA and 50% FA, at dilutions of 1/10, 1/20, and 1/30 (v/v), sprayed at 10 and 25 days after transplanting the tomato plants. Increases were observed in the following parameters: plant height, stem diameter, number of fruits/plants, polar and equatorial fruit diameter, fruit fresh and dry mass, % TSS, maturity index, vitamin C, net profit, and cost ratio benefit, with the 1/30 treatment providing the best results. In addition, Reyes Perez et al. (2011), working with the same product, same application periods, and equal dilutions, adding 1/40 and 1/50 (v/v), did not observe any significant improvement in the evaluated characteristics: pH, % TSS, acidity, vitamin C, and malic acid. Oliveira Amatussi et al. (2020), in addition to the variables mentioned above also observed increases in root fresh and dry weight, root volume, and total root and fine root length. These authors performed foliar spraying of *Lithothamnium* sp., a micronized calcareous alga containing HAs, at doses of 0, 0.75, 1.5, 2.25, and 3.0 g. L^{-1}, and the promotion of shoot growth required higher application concentrations compared to that of the roots. It was found, therefore, that these algae may be another HS-based material with potential biostimulant effects on plants.

An important issue that needs to be addressed to ensure the correct foliar fertilization application procedure with biostimulants is the time of substance application, which needs to occur according to the phenological development stage of the crop. For example, Alfonso et al. (2010), where the HS-based product derived from Biostan vermicompost (25 mg. ha^{-1}) was sprayed, it was observed that under the experimental conditions, there were two best application times for tomato: at the beginning of flowering and at flowering/fruiting, resulting in improvements in the leaf N, P, and K; fruit nitrate levels; flower and fruit number per plant; % TSS; and crop yield (t. ha^{-1}). Similarly, AbdAllah et al. (2018) found that the FA solution (0.15 and 0.20%) applied three times during the fruiting period was effective in acting preventing transpiration, increasing the water use efficiency in tomato plants.

Another interesting point regarding the foliar application of HSs concerns their synergistic effects with plant growth-promoting bacteria. For example, Olivares et al. (2015) observed a significant increase in the root dry mass, roots, and leaf areas, in addition to the levels of PAL, nitrate reductase enzymes, and tomato leaf protein content after foliar spraying of humate derived from cattle manure vermicompost added to a *Herbaspirillum seropedicae,* an endophytic diazotrophic bacterium, suspension. They also found that the combined effects of the HS application with the bacteria at 15 and 30 days after transplanting promoted greater growth of tomato plants, reflecting better fruit yield, increased the nitrogen-fixing population both in the rhizosphere region and in root and leaf tissues. Since in comparison to toher products, HSs are more recalcitrant to microbial activity, they can also be used as carriers of these beneficial organisms in agriculture. These results indicate that this treatment with HSs and plant growth-promoting microorganisms is a very useful tool for increasing sustainable agriculture (Canellas et al., 2015).

In addition to those on tomato, several studies on other fruits have focused on effect of HSs applied via foliage. For cucumber (*Cucumis sativus* L.), there are reports of increases in the antioxidant activity of the fruits, the lipophilic and hydrophilic fractions, total carotenoid and xanthophyll levels, lycopene, B-carotene, and chlorogenic acid (Karakurt et al., 2015), as well as increases in plant height, dry mass, number of leaves/plants, average fruit length, diameter and weight, chlorophyll content, % N, % K, % TSS, and fruit yield (Kazemi 2013). In turn, Abdulbaset and Al-Madhagi (2019) evaluated the spraying of HA (0, 100, and 300 mg. L^{-1}) and yeast extract (0, 2000, and 4000 mg. L^{-1}), applied alone or together, on cucumber plants after one month of cultivation, and they observed an increase in the growth rate but a reduction in chlorophyll content (SPAD); in addition, the best HA treatment was 100 mg. L^{-1}. In addition to stimulating growth, Kamel et al. (2014) found that the foliar application of FA, extracted from biogas manure, (50, 75, and 150 mg. L^{-1}) was effective at all concentrations in controlling downy mildew and powdery mildew in cucumber plants, even more than fungicides. In the cultivation of eggplant (*Solanum melongena* L.), Ebrahim Azarpour (2012) tested the foliar application of HA (0, 25, and 50 mg. L^{-1}) plus mineral and organic nitrogen fertilizers applied to the soil. In this study, in comparison to the other does, the dose of 50 mg. L^{-1} HA was the most efficient in improving fruit yield (t. ha^{-1}), number of fruits per m^2, number of branches/plants, plant height (cm), and the length and width of the fruit (cm). Many studies on the cultivation of pepper (*Capsicum annum* L.) have indicated increases growth (plant height, number of fruits/plants, number of branches/plants, etc.) and yield (Yasar Karakurt et al., 2009; Fathima and Denesh 2013, Jan et al., 2020) (Fig. 4).

4.2. Foliar application of HSs to grasses

Grasses (family Poaceae or Gramineae) are one of the largest families of angiosperms, with more than ten thousand species, and they are represented by plants commonly called grasses and bamboos. This group of plants is of great importance to humans, especially as a source of food as reflected in the current estimate that approximately 70% of the Earth's arable land (or 70 million ha) is intended for cereal cultivation (corn, wheat, oats, rice, etc.). In addition, the species of this family also provide soil cover to protect against erosive processes (Filgueiras 2021). Another relevant aspect of grass use, in addition to legume species (family Fabaceae) use, as tropical forage plants in pastures, is its ability to serve as a food base for ruminants, as perennial plants capable of sprouting after cutting and/or grazing (Souza et al., 2018).

Rice (*Oryza sativa* L.) is one of the most important crops in the world, as it serves as food for more than half of the world's population and is essential for the maintenance of food security. In recent decades, world rice production has increased significantly, largely due to improvements in cultivation technologies (Fu et al., 2021). Thus, there are many studies on rice biofertilization with HSs. The studies performed by Osman et al. (2013) tested the foliar application of HA, FA, or both (HA + FA) (5 g. L^{-1}) in addition to nitrogen fertilization with urea and anhydrous ammonia applied to the soil at 20 and 35 days after transplanting of Giza 101 rice seedlings. There were increases in tiller number/m^2; weight of 1000 grains; grain and straw yield; N, P, K, nitrate, and nitrite contents; and profitability, with the best responses obtained from the combined treatment HA + FA plus anhydrous ammonia. In turn, Hernández et al. (2018) evaluated the foliar spraying of HA derived from cattle manure vermicompost (0, 30, 34, and 38 mg. L^{-1}) applied at 3 mL/plant at 32 days after germination of two rice cultivars (Jucarito104 and IACuba-33) in the active tillering phase under water stress and no water stress conditions. The authors observed positive effects of HA, as evidenced by increases in plant height, root dry mass, peroxidase enzyme activity (POX), and total soluble protein levels under both water conditions. The highest doses (34 and 38 mg. L^{-1} of HA) provided the best results. The authors hypothesized that the possible protective effect of HA against water deficit may develop through an ABA-like action of HS, which would mimic the action of this hormone.

The protective action of HSs was also observed in maize (*Zea mays* L.), where the foliar application of FA (1.5 mg. L^{-1}, 25 mL sprayed) to plants under water stress improved the growth and physiological characteristics of these plants. Malondialdehyde (MDA) is a product of lipid peroxidation (Anjum et al., 2011). Relatedly, Khaled and Fawy (2011) applied an HA solution via foliage (0, 0.1, and 0.2%) and sprayed in 5 L of deionized water at 20 and 40 days after corn seedling emergence, as well as application of HA to the soil (0, 2, and 4 g. kg^{-1}), and both situations increased salt stress. The two forms of HAs attenuated salt stress, increasing the dry weight and the macro- and micronutrient contents, especially from the lowest doses (0.1% foliar and 2 g. kg^{-1} to the soil) to the highest doses, and beneficial effects were reduced. The works of Canellas et al. (2005) studied the influence of HA foliar application together with *H. seropedicae* suspension (50 mg. L^{-1} and 450 L. ha^{-1}) in field experiments and found that spraying improved grain yield (especially in times of drought) and root and shoot biomass.

Regarding wheat (*Triticum aestivum* L.), many studies have also evaluated the foliar application of HS-based materials. Xudan (1986) applied FA solutions (0.01 and 0.05%) to this crop and found greater resistance to drought stress in the treated plants, reducing transpiration through greater stomatal closure. Such effects were also reported later by Dziugieł and Wadas (2020) for the potato crop, and they observed an increase in water, chlorophyll, P uptake, number of grains, and percentage of fertile ears compared to those in untreated wheat plants. In another study, HA (0, 0.1, and 0.2%) was sprayed on wheat leaves at 20 and 35 days after seedling emergence in 5 L of deionized water and sprayed directly on the soil (0, 1, and 2 g. kg^{-1}), with both HAs derived from leonardite, and the soil of the experiment presented limestone conditions, with the addition of increasing amounts of lime. It was observed that the HA supply limited the decrease in dry weight and nutrient absorption caused by the excess lime applied (Katkat et al., 2009).

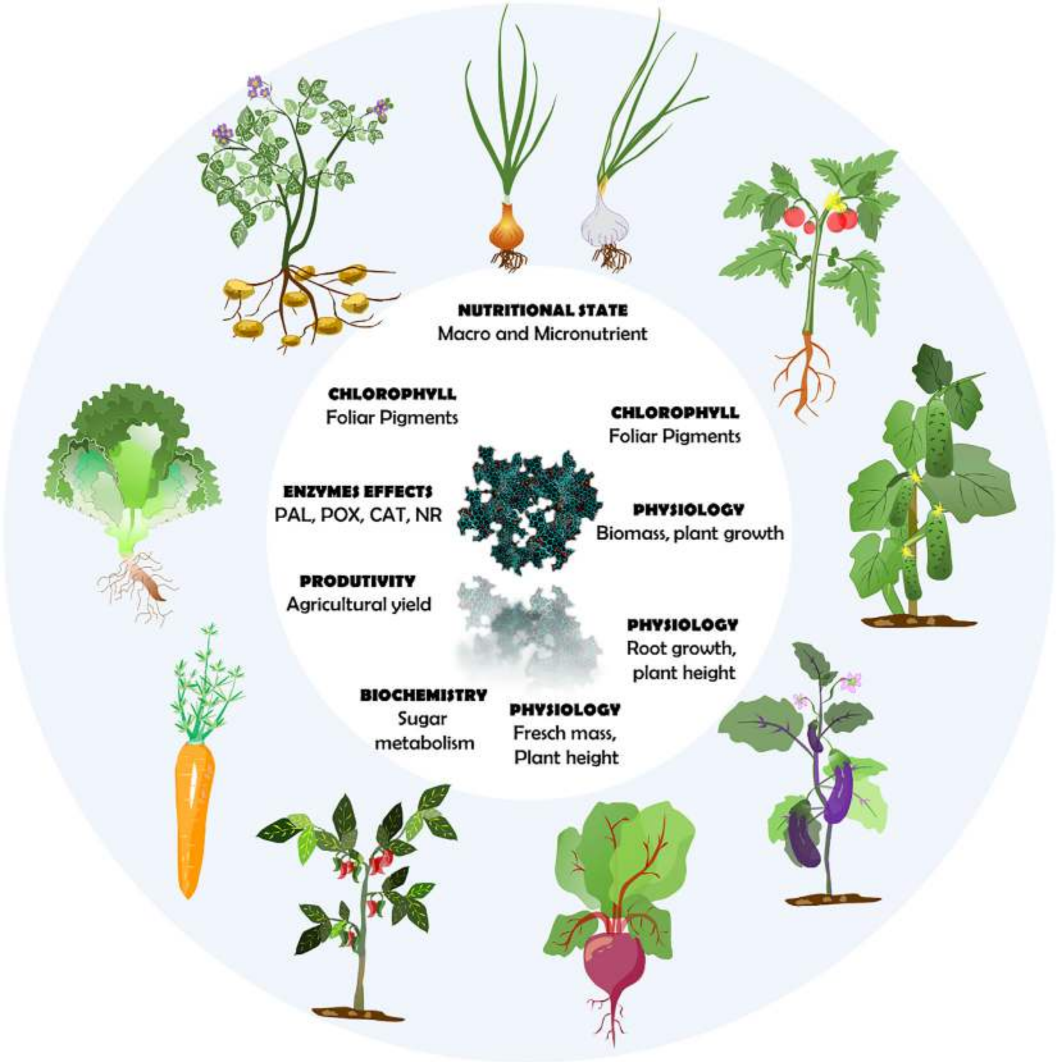

Fig. 4. Main effects of HS foliar application on vegetables.

Positive effects of foliar FA solution application were also observed in this crop, both in terms of a higher bioavailability and concentration of zinc (Zn) in the grains, with the liquid formulation of FA at 0.1% (m/v)(Wang et al., 2020), and in a reduction in the absorption and accumulation of chromium (Cr), with higher activities of antioxidant enzymes, levels of photosynthetic pigments, and plant biomass, after spraying in the tillering and initialization stages with a FA solution at 1.5 mg. L^{-1} (Ali et al., 2015). Delfine et al. (2005) showed that although foliar application of humic extract improved some parameters of durum wheat (*Triticum durum* L.), such as grain yield, number of grains per ear, foliar protein content, and others, it was less effective than fractional N application to the soil.

In Abdulsattar and Fahdawi (2020), the effect of foliar spraying of an HA-based product (0, 250, 500, and 750 mg. L^{-1}) on barley (*Hordeum vulgare* L.) that was applied twice showed effects one month after planting and at the beginning of anthesis. These authors also used different spacings between crop rows. It was found that the application of HA was useful under the conditions of this experiment, resulting in an increase in the number of spikes/m^2, grains/ear, biological and grain yield and harvest index, in addition to a reduction in grain weight. Overall, the intermediate dose of 500 mg. L^{-1} was the most efficient in combination with a row spacing of 15 cm. Testing HS foliar fertilization in oat (*Avena sativa* L. cv. Shaffaa) plants under a field experiment, during the tillering and 50% flowering stages, Alabdulla (2019) observed that treatments with HA (0, 3, 6, and 9 g. L^{-1}) increased the number of panicles/m^2, grains/panicles, % N, %P, %K, and crude protein on a dry matter basis and the grain and forage yields, in addition to reducing the weight of 1000 grains. There was an influence the applied times and doses, and the best results were obtained from spraying at the tillering stage, where the best doses were 6 g. L^{-1} for grain yield and 9 g. L^{-1} for nutritional %. In another study, foliar application of a HS was performed on sorghum (*Sorghum bicolor* L.), where the product Humitron (0.125%) was supplied twice, when the plants reached 30 cm in height and before panicle emergence, as recommended for this species, under saline conditions. An improvement in sorghum growth and yield was observed as a function of HS, with increases in plant height, leaf area, dry weight, panicle dry weight, harvest index, and osmotic potential (Santoyo et al., 1998).

In addition to studies on grain crops, there are also reports of foliar spraying of HSs in grams. For example, Maibodi et al. (2015) tested the influence of a HA from leonardite (0, 100, 400, and 1000 mg. L^{-1}), sprayed monthly for 6 months, on perennial ryegrass (*Lolium perenne* L.), a winter forage species. The authors found that the HS increased the N and iron (Fe) contents in the leaves and the diameter, length, and root surface under low HA concentrations, in addition to plant height and better visual quality under high HA concentrations, without affecting the chlorophyll content. Similar and different results were obtained by Ervin et al. (2008) for the species *Poa pratensis* L. ("Kentucky Bluegrass"), another perennial winter crop, where HA derived from peat (47 g. m^2) and leonardite (58 g. m^2) was applied to leaves 6 (six) times over 12 (twelve) weeks (once every two weeks), at a rate of 375 L. ha^{-1}, in Blacksburg, Virginia, USA, where there is a temperate continental climate. In this study, both HA sources improved strength (kg. m^3) and root mass (mg. m^3) but did not affect visual quality, unlike in a previous study with perennial ryegrass or a study on photochemical efficiency and tiller density. The researchers attributed this lack of effects to greater leaf senescence due to various frost events in the early period of the experiment.

In turn, Cooper et al. (1998) studied the species *Agrostis stolonifera* L. ("creeping bentgrass"), also a winter perennial that is widely used on golf courses because it tolerates close cuts to the soil. These authors found that the foliar application of HA derived from soil, peat, and leonardite and a commercial soluble product (100, 200, and 400 g. L^{-1}, sprayed 3 times) had very limited effects in relation to the granular humate that was applied to the soil, without altering the length and root mass or nutritional contents. According to these researchers, such results were due to the granular humates coming into direct contact with the roots, thus inducing greater root growth compared to HA applied directly to the leaves (Fig. 5).

4.2.1. Foliar application of HS to legumes

Leguminous plants (Fabaceae family) are important sources of protein, phosphorus, and calcium and are therefore fundamental in the diet of thousands of people, especially those in developing countries (Desire et al., 2021). Legumes include small plants (alfalfa, peas, soybeans, and clovers), shrubs (pigweed pigeon pea), and trees, with leguminous fruits and leaf blades (Fontaneli et al., 2009). In addition, most legumes are able to establish a mutualistic association with rhizobia that provide them photoassimilates and nutrients and receive N in the form of ammonium and amino acids (Liu et al., 2018); thus, this biological nitrogen fixation (BNF) is an alternative to using synthetic nitrogen fertilizers, reducing greenhouse gas emissions resulting from the process of fertilizer production, its transport, and its application in crops in the field (Sant'Anna et al., 2018). Legumes are widely used as green manure in crops with greater demand for this nutrient because of their ability to obtain biologically fixed N (Zotarelli et al., 2012). Due to the cited benefits of these crops, many studies have been conducted to evaluate their yields, including through the foliar application of HSs.

Beans (*Phaseolus vulgaris* L.) belong to this family and have high levels of protein, fiber, complex carbohydrates, folic acid, iron, zinc, magnesium, and potassium (Ribeiro et al., 2011). Elkhatib et al. (2020) evaluated the performance of common bean cv. Nebraska in two field experiments in Egypt, after foliar fertilization with HA (1 and 2 g. L^{-1}), FA (2.5 and 5 g. L^{-1}), and tryptophan, a physiological precursor of indoleacetic acid (0.5 and 1 g. L^{-1}), and these were all sprayed twice, 24 days after sowing and at the beginning of flowering. It was found that all biostimulants increased plant height, foliage fresh and dry mass, number of leaves/plants, leaf area, % N, %P, %K, leaf chlorophyll content, the number of pods/plants, pod/plant, seed/plant weight, and seed yield. Tryptophan provided the highest results, followed by FA and HA.

Working with the foliar application of FA (0, 3, 6 and 9 g. L^{-1}) in the fava bean species *Vicia faba* L. at 45 and 60 days after sowing (elongation phase), Abdel-Baky et al. (2019) also observed improvements in the aforementioned culture parameters, with

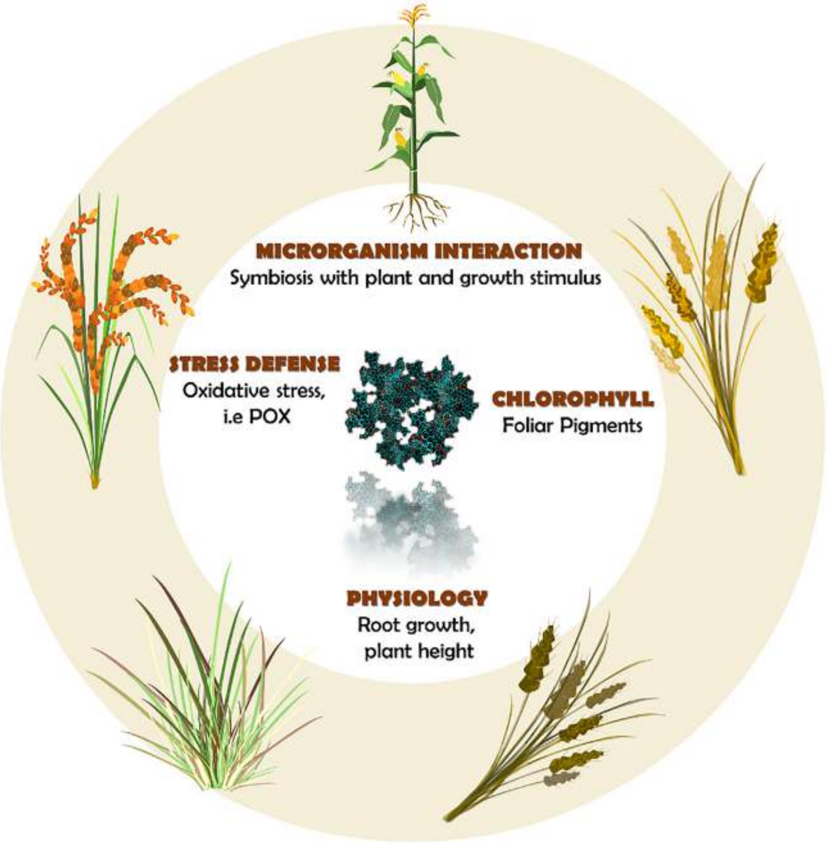

Fig. 5. Main effects of HS foliar application on grasses.

the highest responses obtained at highest FA dose (9 g. L^{-1}). In Kaya et al. (2005), the effects of the foliar application of an HS-based product (at a rate of 2000 mL. ha^{-1}), pretreatment of seeds with zinc, and a combination of the two treatments on common bean were tested. Foliar spraying was performed at the third to sixth leaf stage at night because during the day, the high temperatures caused the plants to transpire more instead of absorbing nutrients. The two application approaches alone did not result in significant effects, but together, they helped increase parameters such as plant height, number of pods/plant, and number of seeds/plant, in addition to the weight of seeds/plant, indicating a synergistic effect between treatments.

Many other leguminous crops of economic interest have already received foliar application of HS. For example, soybean (*Glycine* max L. Merr.) was sprayed with a commercial humic product derived from leonardite at four stages of its development (vegetative: V2, V4, and V6; reproductive: R2, full flowering). Experiments with field tests were performed at three different sites in the state of Iowa, USA. The height of the plants and the oil content of the seeds were not altered in any experiment. Stand density, seed protein content, and crop yield only increased in some evaluated locations (Lenssen et al., 2019). For the cultivation of peas (*Pisum sativum* L.) under increasing conditions of salt stress, Basha et al. (2020) tested soil fertilization with potassium sulfate with and without foliar application of HA (0.2%) applied three times (1, 3, and 5 weeks after transplanting). The authors found improvements in growth and developmental parameters such as plant height, leaf area, and number of pods/plants, in addition to a reduction in the deleterious effects of salinity on chlorophyll *a*, b, and carotenoid levels. In relation to peanuts (*Arachis hypogaea* L.), there are also studies indicating an increase in yields and their components in response to foliar spraying of HA-based products, alone or in some combination of these; an application of the same product to the soil (with foliar treatment at the rate of 1, 1.5, and 2% at 45 days after sowing) or based on Teli et al. (2020) together with diammonium phosphate (DAP-2.0%) and a micronutrient mixture (0.35%), with foliar treatment of 0.3% HA sprayed twice (Reddy et al., 2020).

Meena et al. (2018) investigated the influence of a foliar spray of 15% liquid HA (doses of 1.0, 1.5, 2.5, and 4.0 mL. L^{-1}) at 30, 60 and 90 days after sowing pigeon pea (*Cajanus cajan* (L) Millsp.), a legume shrub. Increases were observed in indices such as leaf area, relative growth rate, net assimilation rate, and total dry matter, and the results increased with the HS dosage. In another study with the same species, the foliar application of HA (1 mL. L^{-1}) occurred once (30 days after sowing) or twice (at 30 and 45 days after sowing), in addition to other treatments with soil applications of HA and compost. In general, the best responses were obtained from soil fertilization; however, in comparison to the control, HA foliar supplies (especially applied twice) also provided increases in parameters such as dry biomass, number of pods/plant and seed yield (Nalia and Sengupta, 2019). In turn, Susithra et al. (2019) tested HA foliar spraying (0.25%) combined with a recommended dose of fertilizer plus phosphobacteria applied to the soil (2 kg. ha^{-1}). The authors also observed significant increases in the aforementioned growth parameters (Fig. 6).

4.2.2. Foliar application of HSs to fruit trees

Fruit production is an important segment of world agricultural production. The world ranking of the countries that produce the most fruit has China in first place, followed by India and Brazil. For example, China contributes 60% of total fresh fruit production, mainly apples, peaches, pears, bananas and oranges (FAOSTAT, 2013). In Brazil the most of these fruit crops are permanent, while the main temporal fruit plants in the country are pineapple, melon, and watermelon (Gerum et al., 2019).

In the same manner already described for the other plant groups, fruit plants are also objects of studies that evaluate the bioactivity of humified materials, including the foliar fertilization of HS. Cavalcante et al. (2011) directly sprayed HA derived from leonardite at rates of 0, 7.5, 15, 22.5, and 30 mL. m^2 at 15, 25 and 30 days after sowing papaya (*Carica papaya* L.) in a covered shelter. The same research group, in a later study, evaluated the foliar application of the same product to yellow passion fruit (*Passiflora edulis* Sims.) (Cavalcante et al., 2013). For both crops, there were increases in plant height, stem diameter, root and shoot dry mass, and chlorophyll levels in leaves. This same team (Silva-Matos et al., 2012) tested foliar application of the same product and at the same dosages in watermelon (*Citrullus lanatus* L.) with different fertilization periods (at 10, 15, and 20 days after sowing). The analyses of the variables were performed 25 days after sowing, and the observed increases in parameters were the same as those indicated in the two previous studies, in addition to increases in root length and volume. Overall, the most responsive dose was 22.5 mL. m^2, with a reduction in beneficial effects being observed with the highest dose.

Ferrara and Brunetti (2010), working with a species of table grape (*Vitis vinifera* L. cv. "Itália"), conducted a foliar application of HA from compost and soil, at concentrations of 5 and 20 mg. L^{-1}. They found that both sources of HSs resulted in an increase in crop yield, berry size, chlorophyll content, N in leaves and petioles, and % TSS and a reduction the in titratable acidity of the fruits and a delay in the degradation of chlorophyll. In a later article, these same authors tested the application of a HA extracted from a sample of clayey soil (100 mg. L^{-1} dose) on the same cultivar at four different times, preflowering, full flowering, fruiting, and "veraison". They found the same responses as those in the previous study and concluded that the treatment at the phenological stage of full flowering showed the greatest differences compared to those in the control (Ferrara and Brunetti 2010). There are also reports of spraying vermicompost HA (30, 40, and 50 mg. L^{-1}) on foliage in the preflowering and fruiting stages of two wine grape cultivars (*Vitis vinifera* cv. Feteasca Regala; *Vitis vinifera* cv. Riesling Italian) in a two-year field experiment in Romania. Higher yields (kg. $vine^{-1}$), photosynthetic rates, chlorophyll *a* and b and carotenoid contents, leaf area, dry and fresh mass of leaves, mass and volume of berries, and % TSS and lower in titratable acidity were observed. Under the conditions of these experiments, the intermediate dose of 40 mg. L^{-1} was the most responsive (Popescu and Popescu 2018).

Higher yields (kg. $tree^{-1}$) were observed after foliar application (among other products) of an HA solution at similar dosages in the following crops: mango (*Mangifera indica* L.) at rates of 0.1, 0.2, and 0.3% sprayed at stage flower bud initiation (Ngullie et al., 2014) and at 0.15, 0.3 and 0.45% applied three times, twice before and once during flowering (El-Hoseiny et al., 2020); peach (P. *persica* L.) at 0.25 and 0.5%, respectively, after fruiting, repeated 4 times at an interval of 15 days (El-Razek et al., 2012); sugar apple (*Annona squamosa* L.), at 1 and 1.5% (Sindha et al., 2018); cashew apple (*Anacardium occidentale* L. at 0.5%, repeated three times in the stages before and after vegetative flushing and during fruiting (Dhanasekaran et al., 2018); *kiwi* fruit (A. *Chev*.) CF Liang and AR Ferguson.) at 0.1 and 0.2%, sprayed three times, before anthesis, after fruiting and at the fruit development stage (Mahmoudi et al., 2014).

The cultivation of pomegranate (*Punica granatum* L.) with HA foliar fertilization (2 and 5 mg. L^{-1}), in addition to the products Kaolin (6%) and 3% calcium-1% boron (CB), all applied alone or together at 30 days after full flowering, had the beneficial effect of reducing the percentage of cracked fruits and increasing fruit weight (Ghanbarpour et al., 2019). For this same culture, Sándor et al. (2015) observed increases in the stem diameter, plant height,

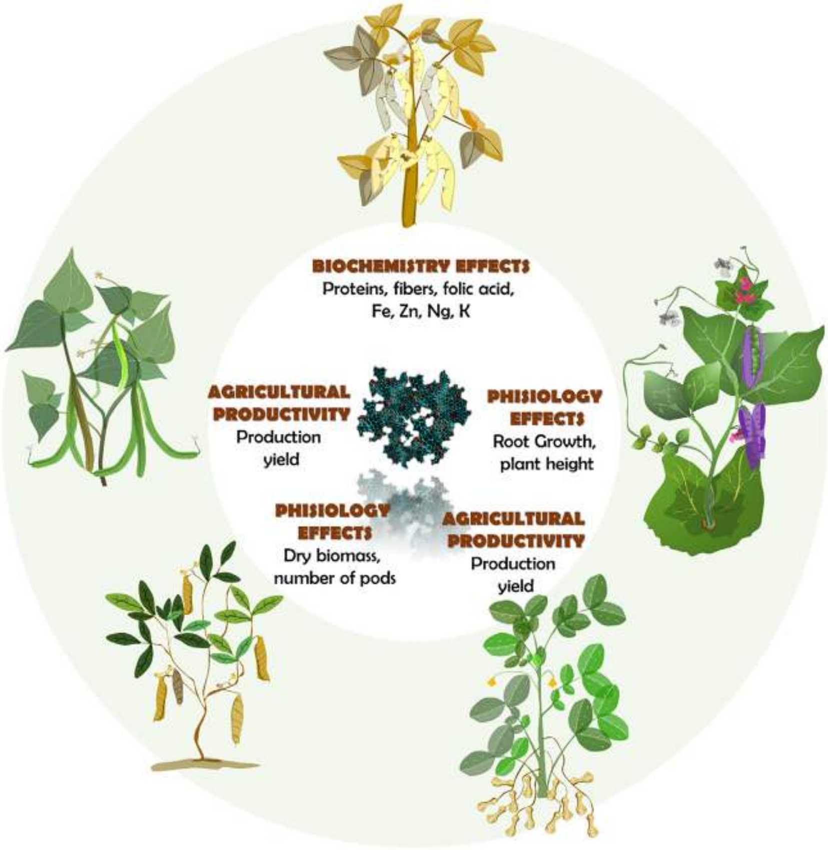

Fig. 6. Main effects of HS foliar application on legumes.

plant weight, and number of roots of pomegranate seedlings treated with foliar FA (10 L. ha^{-1}, 120 days after planting the cuttings in nurseries), in addition to HA on the soil (100 kg. ha^{-1}, divided in two). There were also advantages of HS during the cultivation of guava (*Psidium guajava* L.), where the spraying of potassium humate (0, 2, and 4 mg. L^{-1}) four times, once a week, resulted in increases in the various parameters evaluated (height, stem diameter, number of lateral shoots, and number of leaves/seedlings), in addition to a reduction in the water content of the leaves, with the treatment of 4 mg. L^{-1} being the most responsive (Abdulhameed Ibrahim and Abdulali Al-Sereh 2019).

Foliar and soil applications of HA were also compared in pistachio (*Pistacia vera* L.) crops (40 L. ha^{-1} to the soil; 2.5 L. ha^{-1} to the leaves 3 months after planting (Razavi Nasab et al., 2019) and apricot (*Prunus armeniaca* L.) crops (actosol product, 2.9% HA: 0, 9, and 15 cm^3 on the leaves; 0, 37.5. and 75 cm ^{3} in the soil) (Fathy et al., 2010). Both studies reported increases in growth parameters of the respective species; however, for pistachios, foliar application was more effective, while for apricot, the best treatment was that to the soil. Baldotto et al. (2011), working with pineapple (*Ananas comosus* (L.) Merril), sprayed vermicompost HA (0, 10, 20, and 40 mmol. L^{-1}) plus rock phosphate, with or without the addition of citric acid, to the basal axils of the leaves. Increases in plant height, plant length and width of the middle third of the "D" leaf, diameter of the rosette and base, leaf area and number, and nutrient contents in the shoots were observed (Fig. 7).

4.2.3. Foliar application of HS to oilseeds and medicinal plants

Species that have the ability to accumulate oils in their seeds, especially triacylglycerols, are known as oilseed crops. This storage reserve is later used for the development of seedlings. Such plants are fundamental to the agricultural industry and are useful in food processing and preparation and the production of biodiesel and as raw materials for the synthesis of a variety of products (lubricants, paints, coatings, etc.). The main crops in this group are soybean (already seen in the legume section), sunflower, rapeseed, and palm oil (Zafar et al., 2019). In turn, medicinal plants play an important role in curing various human diseases because they contain bioactive molecules such as simple alkaloids, anthraquinones, naphthopyrone glycosides, phenolic compounds, steroids, and terpenes. Such bioactive substances can be synthesized by both plants and a microbial consortium in their tissues, and these microbes, which reside in plants asymptomatically, are known as endophytes (Yadav and Meena 2021). This category includes, among others, the following species: artichoke, rosemary, chamomile, fennel, eucalyptus, and ginger (Argenta et al., 2011).

Thakur et al. (2017) evaluated the foliar spraying of HA (bud stage) and FA + NPK (floral stage) on sunflower (*Helianthus annuus* L.), with both products sprayed at doses of 0.5 and 1.0%. In addition to the leaf treatment, granular HA (12.5 kg. ha^{-1}) + NPK was also applied to the soil. There was an increase in the N, P, and K contents in the seeds, stems, and soil after harvest, as well as in the soil microbial populations. The HA applied to the soil generated the highest results; however, it was closely followed by the foliar treatments. Shindhe et al. (2020) tested applications of HA (4 ppm) and other organic products (vermicompost and barnyard manure extracts, among others) to foliage, comparing them with inorganic spraying (0.1% boron), with water only, and with the control (no spraying). The treatments were performed at 40 and 60 days after sowing. Increases in plant height, number of leaves, leaf area, leaf dry mass, stem dry mass, head diameter, % of filled achenes, harvest index, test weight (g/100 seeds), and seed (g. plant^{-1}) and total (kg. ha^{-1}) yields. For all these parameters, HA outperformed the control and application with water. However, the humic treat-

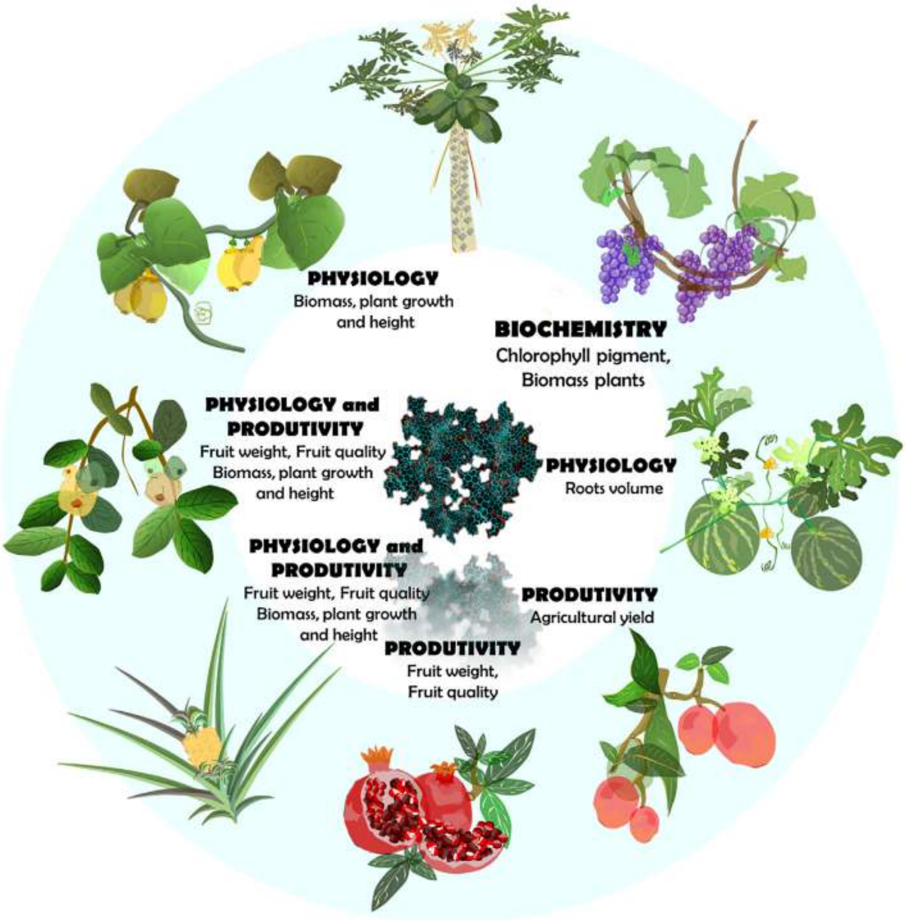

Fig. 7. Main effects of HS foliar application on fruit trees.

ment was only superior to boron in terms of the morphological and growth parameters and was surpassed by most other organic products for all evaluated traits.

Evaluating the influence of HSs on rapeseed (*Brassica napus* L.), Lotfi et al. (2015) applied a FA solution (0, 300, and 600 mg. L^{-1}) to leaves at the vegetative growth and initial flowering stages in well-watered plots with moderate to severe water stress. The authors reported that FA generated an increase in the activities of antioxidant enzymes (SOD, POD, APX, and CAT), a reduction in MDA levels and lipid peroxidation of membranes, and an improvement in the photosynthetic apparatus, with greater quantum efficiency than photosystem two (PSII). In turn, Amiri et al. (2020), studying this same species, tested foliar spraying of the product Humax 95 - WSG (80% HA and 15% AF) at 0.3% at two stages, the 4–6 leaf stage and bud formation. Higher seed and oil yields, increased oleic and linoleic acid contents, and reduced linolenic acid, erucic acid, and glucosinolate contents were observed. In a flax crop (*Linum usitatissimum* L.), Bakry et al. (2013) applied HA (0 and 15 mg. L^{-1}) via the leaves at 45 and 60 days after sowing, in addition to organic fertilization to the soil. Increases in parameters such as plant height, root and shoot fresh and dry mass, root length, %TSS, polysaccharide contents, IAA, total phenols, and biological, seed, oil, and % yield were observed. Regarding the cultivation of olive trees (*Olea europaea* L.), foliar fertilization with HSs provided increases in foliar nutrient contents (Fernández-Escobar et al., 1996), chlorophyll, carbohydrates, proteins, fiber, and fat (Alshamlat et al., 2020).

For medicinal species, there are also many studies of the efficiency of foliar application of HSs. In sesame (*Sesamum indicum* L.), increases in growth parameters and seed yield (Vani et al., 2017) and leaf N, P, K, and chlorophyll contents and % seed oil were observed (Deotale et al., 2019). Safaei et al. (2014) tested fertilization in the leaves of black cumin (*Nigella sativa* L.) with the super humic product (37% HA + FA, doses of 0, 1, 3 and 6 mg. L^{-1}), applied three times, starting at the stage with 8–10 leaves and continuing once every two weeks, until after flowering. The authors identified a higher number of capsules/plants, number of seeds/capsules, weight of seeds/plant, seed and biological yield, and harvest index. In general, the highest doses (3 and 6 mg. L^{-1}) generated the best results. Peppermint (*Mentha* × *piperita* L.) received an HS application to the soil and shoots, and in the latter case, a dose of 1.5 mg. L^{-1} of the product (12% HA and 4% PA), four times at 15-day intervals, was applied starting fifteen days after transplanting. These two humic fertilization methods were combined with inoculation of arbuscular mycorrhizal fungi (AMF) and the addition of chemical fertilizer. The treatments with HSs increased the growth and development parameters, in addition to TSSs, soluble phenolics, chlorophyll *a* and b, carotenoids, starch, and total soluble protein levels, as well as antioxidant power. A reduction in root colonization by AMF was also observed after the humic treatments. Overall, HS foliar application was more effective than soil application and, together with AMF inoculation, was more beneficial than chemical fertilization (Shahabivand et al., 2018). Increments in traits related to the growth and yield of flower heads and chamomile oil (*Matricaria chamomilla* L.) were also reported after foliar application of HA (0, 50, 100, and 150 mg. L^{-1}) at 30 and 60 days after transplanting (Hassan and Fahmy 2020).

Other species of medicinal plants have also benefited from foliar fertilization with HSs; for example, turmeric (*Curcuma longa* L.) received 0.1% potassium humate (31.8% HA) at 90 and 120 days after sowing and increased its absorption of sulfur (S) (Baskar and Sankaran 2004); fennel (*Foeniculum vulgare* Mill.), which also received potassium humate (0, 2, 3, 4, and 5 cm/L) 6 and 8 weeks after planting, increased its vegetative growth parameters and the chemical composition of its leaves (El-Sawy et al., 2021); stevia (*Stevia rebaudiana* Bertoni), received FA leonardite spraying (500 mg. L^{-1}) once every two weeks after transplanting, where in addition to the positive effects on growth, a higher % of steviol glycosides (sweetening species) and a reduction in the diversity of the endophytic bacterial community, with a greater presence of beneficial bacteria and a smaller number of potential pathogens were observed (Yu et al., 2015); vinegar/rosella (*Hibiscus sabdariffa* L.) received a foliar application of potassium humate 80% HA (0, 1, 2 and 3 g. L^{-1}) at 60, 75, and 90 days after sowing (Amin and Kanimarani 2020) and spraying of the Helpstar product (12% HA) at 2 cm. L^{-1} twice at a monthly interval (Ahmed et al., 2011). In both studies, there were improvements in the parameters of vegetative growth (Fig. 8).

4.2.4. Foliar application of HS to ornamental plants

Ornamental plants are recognized for their flowers, shapes, leaf colors, and other attractive aspects, thus contributing to the beautification of environments (Pereira et al., 2018). Floriculture is the production of flowers for commercialization purposes, which, despite being considered by many to be a superfluous activity, serves economic and social functions, as it generates jobs and provides cultural and ecological functions (Terra and Oliveira 2013).

In one of the oldest studies on foliar fertilization with HS, Sladky (1959) tested HS application to begonia plants (*Begonia semperflorens* Link and Otto) with three humic fractions: alcoholic extract, HA, and FA (all at 100 mg/L). The author of that study found that FA was the humic component that generated the best results, increasing plant height, root and shoot dry and fresh mass, oxygen consumption rate, and leaf chlorophyll content. Cultivating chrysanthemum (*Chrysanthemum indicum* L.), Mazhar et al. (2012) evaluated the foliar application of potassium humate (0, 1, 1.5, and 2.0%) twice under conditions of increasing salt stress. The humic treatment increased plant tolerance to saline stress, reduced damage, and increased plant height, stem diameter, number of branches/plants, root and shoot dry and fresh, number of flowers/plants, pedicel length, flower dry and fresh mass, and % of carbohydrates, proteins, N and K. The % proline and sodium (Na) decreased, and the highest dose of potassium humate (2%) generated the best responses of all traits evaluated under any salinity level. Fan et al. (2014) conducted experiments that sprayed HA derived from plant residue sediments (1:600 (v/v)) in a greenhouse on another chrysanthemum species (*Chrysanthemum morifolium* R.), which received treatments at 15, 30, 45, and 60 days after transplantation. In addition to the increases in morphological parameters mentioned in the previous study, the authors of this

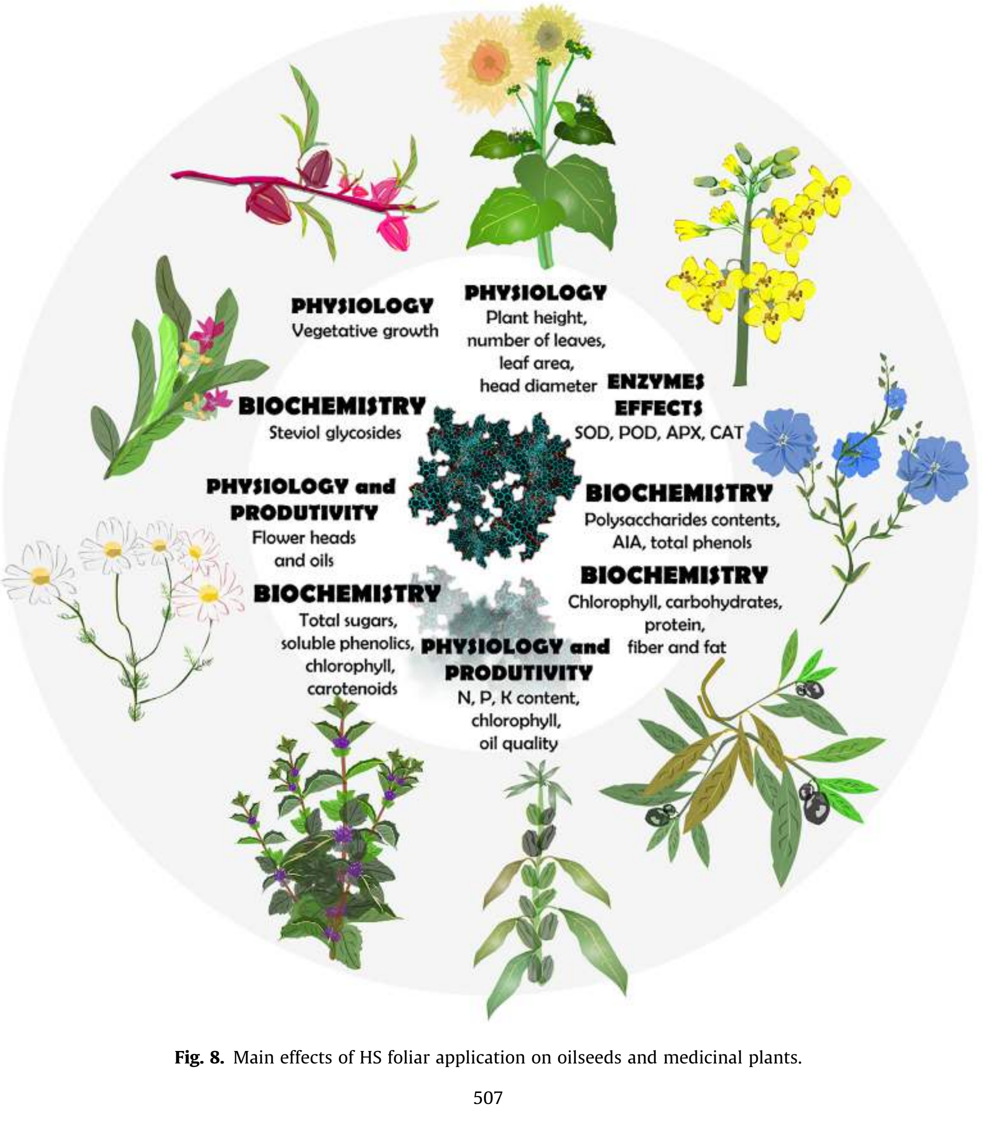

Fig. 8. Main effects of HS foliar application on oilseeds and medicinal plants.

study reported increases in the photosynthetic apparatus of the plants with HA application, as shown by the increases in the rates of net photosynthesis, chlorophyll fluorescence, and chloroplast ultrastructure.

For marigolds (*Calendula officinalis* L.), HA foliar application resulted in improvements in morphological traits, increasing leaf length, number of flowers/plant, and flower width and length (Ahmad et al., 2019), number of leaves/plant, number of main and lateral branches/plant, plant propagation (cm), chlorophyll content in leaves, root and shoot dry and fresh mass, root length, number of days of inflorescence, number of inflorescences/plant, stem length, diameter, number of flowers, and inflorescence dry and fresh mass, and vase life (Hasan 2019). For the African marigold (*Tagetes erecta* L.), these same effects were observed with the spraying of HA and zinc sulfate (both at 0.2%, at 30 and 45 days after planting) combined with the supply of the recommended dose of NPK through fertigation (Das et al., 2020).

Najarian, Souri and Nabigol (2022) reported that the application of HA, mainly at a dose of 250 mg L^{-1}, benefited the development of Pelargonium × hortorum, increasing vegetative growth and flowering characteristics, such as the number of leaves, shoots and flowering and flowers per plant. Other parameters such as length and diameters of the flowering bud, and concentration of foliar mineral elements were also benefited. In turn, Boogar et al. (2014), working with petunia (*Petunia hybrida* L.) observed that spraying HA (0, 100, 300, 600, and 900 ppm) during two development stages resulted in a higher leaf area index, number of tillers and flowers, relative water content, and leaf levels of micronutrients (Fe, Zn, Cu, and Mn), in addition to the improvements mentioned in the previous species. Jawad and Majeed (2017) found increases in morphological parameters and vase life of gerbera (*Gerbera jamesonii* L.) after foliar application of HA (0, 5, 7.5, and 10 mg. L^{-1}) alone or with calcium chloride at different concentrations. In general, the highest HA dose (10 mg. L^{-1}) together with the highest amounts of calcium chloride yielded the best results. In a gladiolus crop (*Gladiolus grandiflorus* L.), the effects of HA extracted from leonardite applied to the soil at planting or directly to the foliage at the 3- and 6-leaf stages added to the soil were studied.

This triple combination resulted in responses such as a high number of leaves/plants, leaf area, chlorophyll contents, stem and ear length and pot life, in addition to reduced shoot emergence (Fig. 9).

5. Conclusions

Foliar treatment with HSs has the potential to generate positive responses in the most diverse crops of agricultural, ornamental and

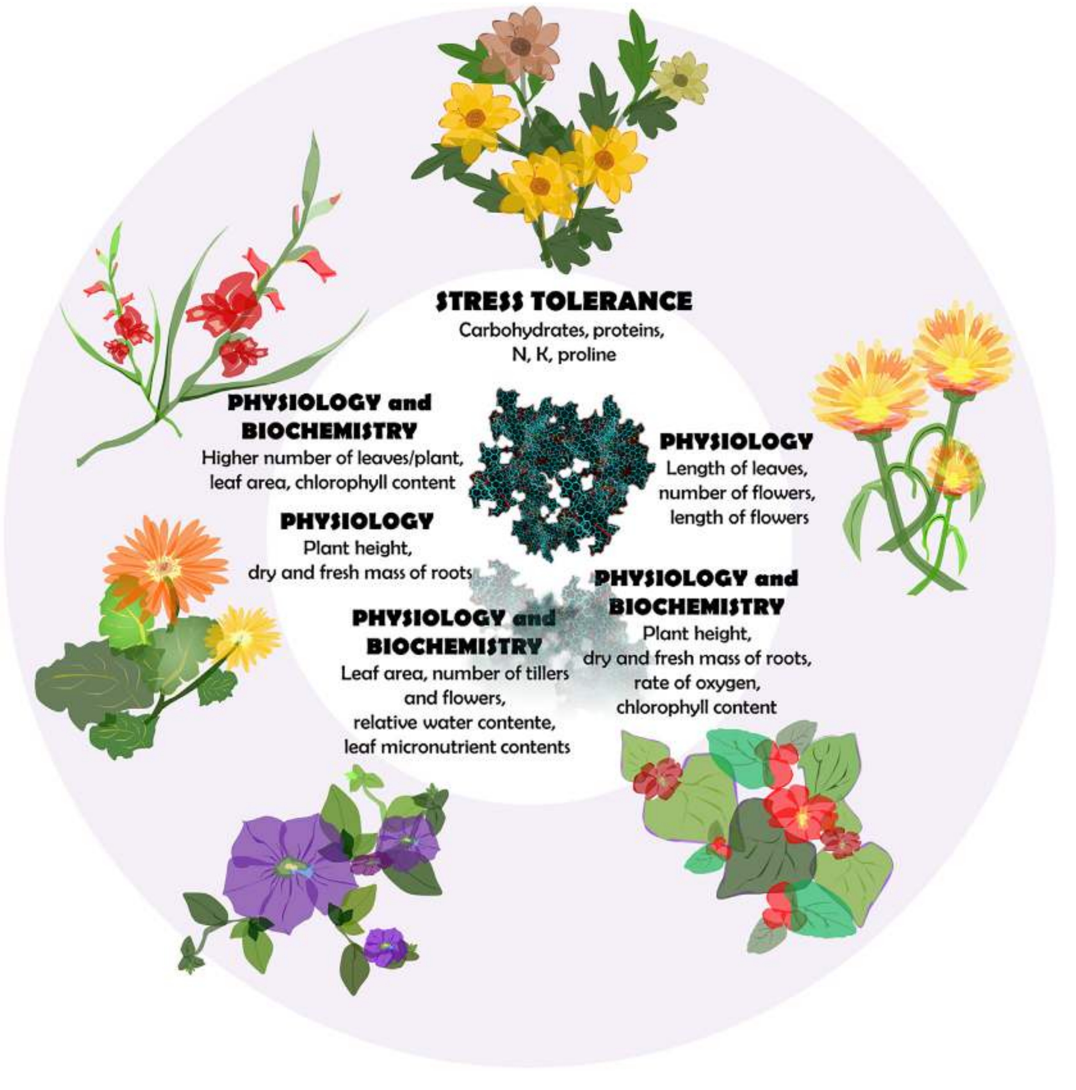

Fig. 9. Main effects of HS foliar application on ornamental plants.

medicinal interest, improving growth and development parameters, as well as physiological characteristics and stress responses. However, due to the great structural complexity of HSs and the fact that they are derived from varied sources, their effects differ, even when applied to the same plant species. This scenario is due to the origin of the humic material applied, its dose, the phenological stage at which the spraying occurs, the number of applications, the characteristics inherent to each plant species, and the experimental and environmental conditions of each location. Thus, there are studies in which the best results were obtained from the highest HS doses, while in other studies, the lower HS doses were more effective. Another point relates to the differences between soil and foliar treatments, with evidence that these two forms of fertilization use distinct mechanisms that result in the observed beneficial effects. Although both approaches are able to increase production, some studies showed that application to the soil is more efficient, while other studies indicated that foliar spraying was better, in addition to reports of a complementary action between these two modalities. Therefore, given this information, HS foliar application can be used as an alternative for more sustainable production systems of most species with economic relevance. However, the specificities of each situation considered here provide information for assisting in appropriated selecting the best way of spraying these materials, aiming at a greater cost-benefit ratio for these activities.

Authors' contributions

All authors contributed equally to the preparation, writing and revision of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro - Brazil (Grant no.SisFAPERJ: 2012028010), the Conselho Nacional de Desenvolvimento Científico e Tecnológico - Brazil (CNPQ:No. 402396/2021-9 Universal 18/2021, CNPq-No. 309722/2021-7, PQ -2 Research grant). Post-Graduate Program in Agronomy - Soil Science at the Federal Rural University of Rio de Janeiro (PPGA -CS, UFRRRJ) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (Grant no. CAPES:001).

References

AbdAllah, A.M., Burkey, K.O., Mashaheet, A.M., 2018. Reduction of plant water consumption through anti-transpirants foliar application in tomato plants (Solanum lycopersicum L). Sci. Hortic. 235, 373–381. https://doi.org/10.1016/j.scienta.2018.03.005.

Abdel-Baky, Y.R., Abouziena, H.F., Amin, A.A., Rashad El-Sh, M., Abd El-Sttar, A.M., 2019. Improve quality and productivity of some faba bean cultivars with foliar application of fulvic acid. Bull. Georgian Acad. Sci. Natl. Res. Cent. 43 (1). https://doi.org/10.1186/s42269-018-0040-3.

Abdel-Razzak, H.S., El-Sharkawy, G.A., 2013. Effects of biofertilizer and humic acid applocations on growth, yield, quality and storability of two garlic (Allium sativum L.) cultivars. Asian. J. Crop. Sci. 5 (1), 48–64. https://doi.org/10.3923/ajcs.2013.48.64.

Abdulbaset, I., Al-Madhagi, H., 2019. Effect of humic acid and yeast on the yield of greenhouse cucumber. J. hortic. Postharvest Res. 2 (1), 67–82. https://doi.org/10.22077/jhpr.2018.1773.1029.

Abdulhameed Ibrahim, M., Abdulali Al-Sereh, E., 2019. Effect of foliar spray with potassium humate and green tea extract on some ofthe vegetative characteristics of guava (Psidium guajava L. Cv. Local) seedlings. Plant Arch. 19 (1), 404–408.

Abdulsattar, W., Fahdawi, E., 2020. Effect of humic acid on growth and yield of barley humic acid as interacted with row spacing project. Indian J. Ecol 47, 62–65.

Abido, W.A.E., Ibrahim, M.E.M., 2017. Role of foliar spraying with biostimulants substances in decreasing mineral nitrogen fertilizer of sugar beet. J. Plant Production Mansoura Univ. 8, 1335–1343. https://doi.org/10.21608/jpp.2017.41994.

Ahmad, S., Khan, J.A., Jamal, A., 2019. Response of pot marigold to different applied levels of humic acid. J. Horticulture Plant Res. 5, 57–60. https://doi.org/10.18052/www.scipress.com/jhpr.5.57.

Ahmad, I., Saquib, R.U., Qasim, M., Saleem, M., Khan, A.S., Yaseen, M., 2013. Humic acid and cultivar effects on growth, yield, vase life, and corm characteristics of gladiolus. Chil. J. Agric. Res. 73 (4), 339–344. https://doi.org/10.4067/S0718-58392013000400002.

Ahmed, Y.M., Shalaby, E.A., Shanan, N.T., 2011. The use of organic and inorganic cultures in improving vegetative growth, yield characters and antioxidant activity of roselle plants (Hibiscus sabdariffa L.). Afr. J. Biotechnol. 10 (11), 1988–1996. https://doi.org/10.5897/AJB10.876.

Akladious, S.A., 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. Sci. Hortic. 236, 244–250. https://doi.org/10.1016/j.scienta.2018.03.047.

Alabdulla, S.A., 2019. Effect of foliar application of humic acid on fodder and grain yield of oat (Avena sativa l.). Crop. Res. 20 (4), 880–885. https://doi.org/10.31830/2348-7542.2019.130.

Albuzio, A., Nardi, S., Gulli, A., 1989. Plant growth regulator activity of small molecular size humic fractions. Sci. Total Environ.. 81 (82), 671–674. https://doi.org/10.1016/0048-9697(89)90176-9.

Alfonso, E.T., Padrón, J.R., Diaz de Armas, M.M., 2010. Respuesta del cultivo del tomate (*Solanum licopersicon* L) a la aplicación foliar de un bioestimulante derivado del Vermicompost. Temas de Ciência y Tecnologia 14 (41), 27–32.

Alhariri, A., Boras, M., 2020. Responses of seed germination and yield related traits to seed pretreatment and foliar spray of humic and amino acids compounds in carrot (*Daucus carota* L.). Int. J. Chem. Stud 8 (4), 26–30. https://doi.org/10.22271/chemi.2020.v8.i4a.10338.

Ali, S., Bharwana, S.A., Rizwan, M., Farid, M., Kanwal, S., Ali, Q., Ibrahim, M., Gill, R.A., Khan, M.D., 2015. Fulvic acid mediates chromium (Cr) tolerance in wheat (Triticum aestivum L.) through lowering of Cr uptake and improved antioxidant defense system. Environ. Sci. Pollut. Res. 22 (14), 10601–10609. https://doi.org/10.1007/s11356-015-4271-7.

Al-Jaf, H.I., Raheem, S.M., Tofiq, G.K., 2018. Growth and Yield of Broccoli (Brassica oleracea L. Var. Corato) as affected by humic acid application. J. Plant Production, Mansoura Univ. 9, 739–741. https://doi.org/10.21608/jpp.2018.36398.

Alshamlat, R.A., Makhoul Makhoul, G., Naddaf, M., Zidan, A., 2020. Effect of foliar application of humic acid and the element, boron and zinc in the components of the olive leaves (khodeiry variety). Int. J. Agric. Environ. Inf. 7 (3), 9–16.

Amador, H.V., Guridi Izquierdo, F., Padrón, V.V., 2018. Revisión bibliográfica las sustancias húmicas como bioestimulantes de plantas bajo condiciones de estrés ambiental. Cultivos Tropicales 39 (4), 102–109.

Amin, M.I.M., Kanimarani, S.M.S., 2020. Impact of foliar application of humic acid and the measure time on growth and production of Roselle Hibiscus sabdariffa. J. Agric. Sci. 20 (1), 38–48.

Amiri Forotaghe, Z., Souri, M.K., Ghanbari Jahromi, M., Mohammadi Torkashvandi, A., 2022. Influence of humic acid application on onion growth characteristics under the water deficit conditions. J. Plant Nutr. 45 (7), 1030–1040.

Amiri, M., Rad, A.H.S., Valadabadi, A., Sayfzadeh, S., Zakerin, H., 2020. Response of rapeseed fatty acid composition to foliar application of humic acid under different plant densities. Plant Soil Environ. 66 (6), 303–308. https://doi.org/10.17221/220/2020-PSE.

Anjum, S.A., Xie, X.-Y., Wang, L.-C., Saleem, M.F., Man, C., Lei, W., 2011. Morphological, physiological and biochemical responses of plants to drought stress. Afr. J. Agric. Res. 6 (9), 2026–2032. https://doi.org/10.5897/AJAR10.027.

Argenta, S.C., Argenta, L.C., Giacomelli, S.R., Cezarotto, V.S., 2011. Plantas medicinais: cultura popular versus ciência medicinal plants: popular culture versus science. Vivências 7, 51–60.

Asli, S., Neumann, P.M., 2010. Rhizosphere humic acid interacts with root cell walls to reduce hydraulic conductivity and plant development. Plant Soil 336 (1), 313–322. https://doi.org/10.1007/s11104-010-0483-2.

Azarpour, E., 2012. Effects of bio, mineral nitrogen fertilizer management, under humic acid foliar spraying on fruit yield and several traits of eggplant (*Solanum melongena* L.). African J. Agric. Res. 7 (7). https://doi.org/10.5897/ajar11.1833.

Bakry, A.B., Sadak, S.h., Moamen, H.T., Abd El Lateef, E.M., 2013. Influence of humic acid and organic fertilizer on growth, chemical constituents, yield and quality of two flax seed cultivars grown under newly reclaimed sandy soils. Int. J. Acad. Res. 5 (5), 125–134. https://doi.org/10.7813/2075-4124.2013/5-5/a.17.

Baldotto, M.A., Giro, V.B., Baldotto, L.E.B., Canellas, L.P., Velloso, A.C.X., 2011. Initial performance of pineapple and utilization of rock phosphate applied in combination with organic compounds to leaf axils. Revista Ceres 58 (3), 393–401. https://doi.org/10.1590/s0034-737x2011000300021.

Balmori, D.M., Domínguez, C.Y.A., Carreras, C.R., Rebatos, S.M., Farías, L.B.P., Izquierdo, F.G., Berbara, R.L.L., García, A.C., 2019. Foliar application of humic liquid extract from vermicompost improves garlic (Allium sativum L.) production and fruit quality. Int. J. Recycling Organic Waste Agric. 8, 103–112. https://doi.org/10.1007/s40093-019-0279-1.

Basha, D.M.A., Hellal, F., El-Sayed, S., 2020. Effects of potassium and humic acid on amelioration of soil salinity hazardous on pea plants. Asian J. Soil Sci. Plant Nutr. 1–10. https://doi.org/10.9734/ajsspn/2019/v5i430073.

Baskar, K., Sankaran, K., 2004. Effect of lignite humic acid on available S and its uptake in turmeric. Agropedology. 14.

Boldrin, P.F., Faquin, V., Ramos, S.J., Boldrin, K.V.F., Ávila, F.W., Guilherme, L.R.G., 2013. Soil and foliar application of selenium in rice biofortification. J. Food Compos. Anal. 31 (2), 238–244. https://doi.org/10.1016/j.jfca.2013.06.002.

Boogar, A.R., Shirmohammadi, E., Geikloo, A., 2014. Bulletin of environment, pharmacology and life sciences effect of humic acid application on qualitative characteristic and micronutrient status in Petunia hybrid L. Env. Pharmacol. Life Sci. 3, 15–19.

Boussingault, J.B., 1868. Action deletere de la vapeur du mercure sur les plantes. Agronomie 4, 343–359.

Brongniart, A., 1834. Sur l'epiderme des plantes. Nouvelles r ´echerches sur lastructure de l'epiderm des v´eg´etaux. Ann. Sci. Nat. (Bot) 1, 65–71.

Burkhardt, J., Basi, S., Pariyar, S., Hunsche, M., 2012. Stomatal penetration by aqueous solutions - an update involving leaf surface particles. New Phytol. 196 (3), 774–787. https://doi.org/10.1111/j.1469-8137.2012.04307.x.

Bustamante Eguiguren, S., Nguyen, H.A., Caldwell, A., Nolin, K.A., Wu, C.A., 2020. Convergence of glandular trichome morphology and chemistry in two montane monkeyflower (Mimulus, Phrymaceae) species. Flora: Morphology, Distribution, Funct. Ecol. Plants 265. https://doi.org/10.1016/j.flora.2020.151567.

Camargo Junior, O. A., Brandão Junior, J. U. T., Santos, H. S., Freitas, P. S. L. de. 2018. Hortaliças-fruto: aspectos gerais e uma estimativa da produção científica. In: Hortaliças-fruto. pp. 23–35. EDUEM.

Canellas, L.P., Ferreira Da Silva, S., Lopes Olivares, F., 2005. Foliar application of Herbaspirillum seropedicae and humic acid increase maize yields. J. Food Agric. Environ. 13, 146–153.

Canellas, L.P., Olivares, F.L., Aguiar, N.O., Jones, D.L., Nebbioso, A., Mazzei, P., Piccolo, A., 2015. Humic and fulvic acids as biostimulants in horticulture. Sci. Hortic. 196, 15–27. https://doi.org/10.1016/j.scienta.2015.09.013.

Cavalcante, Í.H.L., da Silva, R.R.S., Albano, F.G., de Lima, F.N., Marques, A.S., 2011. Foliar spray of humic substances on seedling production of papaya (pawpaw). J. Agron. 10 (4), 118–122. https://doi.org/10.3923/ja.2011.118.122.

Cavalcante, I.H.L., Silva-Matos, R.R.S., Albano, F.G., Silva Júnior, G.B., Silva, A.M., Costa, L.S., 2013. Foliar spray of humic substances on seedling production of yellow passion fruit. J. Food Agric. Environ. 11 (2), 301–304.

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., Kim, W.Y., 2020. Humic acid enhances heat stress tolerance via transcriptional activation of Heat-Shock Proteins in Arabidopsis. Sci. Rep. 10 (1). https://doi.org/10.1038/s41598-020-71701-8.

Chen, Y., Aviad, T., 1990. Effects of humic substances on plant growth. In: MacCarthy, P. (Ed.), Humic substances in soil and crop science: selected readings. Madison, Wisconsin, pp. 161–186.

Cooper, R.J., Liu, C., Fisher, D.S., 1998. Influence of humic substances on rooting and nutrient content of creeping bentgrass. Crop Sci. 38 (6), 1639–1644. https://doi.org/10.2135/cropsci1998.0011183X003800060037x.

Cristofano, F., El-Nakhel, C., Rouphael, Y., August 1.. Biostimulant substances for sustainable agriculture: Origin, operating mechanisms and effects on cucurbits, leafy greens, and nightshade vegetables species. Biomolecules. https://doi.org/10.3390/biom11081103.

da Silva Pereira, J., dos Santos Silva, D.L., da Silva, G.S., dos Santos Oliveira, D., 2018. Plantas ornamentais ocorrentes no município de aldeias altas, Maranhão, Brasil. Acta Tecnológica 13 (1), 79–93. https://doi.org/10.35818/acta.v13i1.612.

Das, S., Rahman, F.H., Sengupta, T., Nag, K., 2020. Studies on the response of african marigold (Tagetes erecta) to npk, humic acid and zinc sulphate in red and lateritic soils of Jhargarm district of west bengal. Adv. Res.

de Aguiar, T.C., de Oliveira Torchia, D.F., de Castro, T.A.V.T., Tavares, O.C.H., de Abreu Lopes, S., da Silva, L.D.S., Castro, R.N., Berbara, R.L.L., Pereira, M.G., García, A.C., 2022. Spectroscopic–chemometric modeling of 80 humic acids confirms the structural pattern identity of humified organic matter despite different formation environments. Sci. Total Environ. 833. https://doi.org/10.1016/j.scitotenv.2022.155133.

de Castro, T.A.V.T., Berbara, R.L.L., Tavares, O.C.H., da Graça Mello, D.F., Pereira, E.G., de Souza, C.D.C.B., Espinosa, L.M., 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 Physiol. Biochem. 162, 171–184. https://doi.org/10.1016/j.plaphy.2021.02.043.

de Hita, D., Fuentes, M., Fernández, V., Zamarreño, A.M., Olaetxea, M., García-Mina, J. M., 2020. Discriminating the short-term action of root and foliar application of humic acids on plant growth: emerging role of jasmonic acid. Front. Plant Sci. 11. https://doi.org/10.3389/fpls.2020.00493.

de Souza, E.L., da Cruz, P.J.R., Bonfá, C.S., Magalhães, M.A., 2018. Plantas forrageiras para pastos de alta produtividade Bovinocultura, equideocultura, forragem, ovinocaprinocultura, produção. Nutri Time 15 (4), 8272–8284.

del Amor, F.M., Cuadra-Crespo, P., 2011. Gas exchange and antioxidant response of sweet pepper to foliar urea spray as affected by ambient temperature. Sci. Hortic. 127 (3), 334–340. https://doi.org/10.1016/j.scienta.2010.10.028.

Delfine, S., Tognetti, R., Desiderio, E., Alvino, A., 2005. Effect of foliar application of N and humic acids on growth and yield of durum wheat. Agronomie 25 (2), 183–191. https://doi.org/10.1051/agro:2005017.

Demidchik, V., Shabala, S.N., Davies, J.M., 2007. Spatial variation in H_2O_2 response of Arabidopsis thaliana root epidermal Ca^{2+} flux and plasma membrane Ca^{2+} channels. Plant J. 49 (3), 377–386. https://doi.org/10.1111/j.1365-313X.2006.02971.x.

Deotale, R.D., Guddhe, V.A., Kamdi, S.R., Patil, S.R., Madke, V.S., Baviskar, S.B., Meshram, M.P., 2019. Response of humic acid through vermicompost wash and naa on chemical, biochemical, yield and yield contributing parameters of sesamum. J. Soils Crops.

Desire, M.F., Blessing, M., Elijah, N., Ronald, M., Agather, K., Tapiwa, Z., Florence, M. R., George, N., March 1.. Exploring food fortification potential of neglected legume and oil seed crops for improving food and nutrition security among smallholder farming communities: a systematic review. J. Agric. Food. https://doi.org/10.1016/j.jafr.2021.100117.

Dhanasekaran, K., Elayaraja, D., Srinivasan, S., 2018. Effect of foliar application of micronutrients enriched humic acid and gibberellic acid on the fruit and nut yield of cashew. JETIR 5 (5), 771–773.

dos Santos, A.C.M., Rodrigues, L.U., de Andrade, C.A.O., da Carneiro, J.S., da Silva, R.R., 2018. Ácidos húmicos e nitrogênio na produção de mudas de alface. Revista Brasileira de Tecnologia Aplicada Nas Ciências Agrárias 11 (1). https://doi.org/10.5935/paet.v11.n1.08.

Duan, D., Tong, J., Xu, Q., Dai, L., Ye, J., Wu, H., Xu, C., Shi, J., 2020. Regulation mechanisms of humic acid on Pb stress in tea plant (*Camellia sinensis* L.). Environ. Pollut. 267. https://doi.org/10.1016/j.envpol.2020.115546.

Dziugieł, T., Wadas, W., 2020. Possibility of increasing early crop potato yield with foliar application of seaweed extracts and humic acids. J. Cent. Eur. Agric. 21 (2), 300–310. https://doi.org/10.5513/JCEA01/21.2.2576.

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. J. Horticultural Sci. Ornamental Plants 10 (3), 159–166. https://doi.org/10.5829/idosi.jhsop.2018.159.166.

El-Hoseiny, H.M., Helaly, M.N., Elsheery, N.I., Alam-Eldein, S.M., 2020. Humic acid and boron to minimize the incidence of alternate bearing and improve the productivity and fruit quality of mango trees. HortSci. 55 (7), 1026–1037. https://doi.org/10.21273/HORTSCI15053-20.

Elkhatib, H.A., Gabr, S.M., Roshdy, A.H., Kasi, R.S., 2020. Effects of different nitrogen fertilization rates and foliar application of humic acid, fulvic acid and tryptophan on growth, productivity and chemical composition of common bean plants (Phaseolus vulgaris L.). Alexandria Sci. Exchange J. 41 (2), 191–204. https://doi.org/10.21608/asejaiqjsae.2020.93900.

El-Sawy, S.M., El-Bassiony, A.M., Fawzy, Z.F., Shedeed, S.I., 2021. Improving yield, physical and chemical qualities of sweet fennel bulbs by spraying of potassium humate. J. Horticultural Sci. Ornamental Plants 13 (3), 272–281. https://doi.org/10.5829/idosi.jhsop.2021.272.281.

Ervin, E.H., Zhang, X., Roberts, J.C., 2008. Improving root development with foliar humic acid applications during kentucky bluegrass sod establishment on sand. Acta Hort 783, 317–322.

Eskandari, S., Sharifnabi, B., 2020. Foliar spray time affects the efficacy of applied manganese on enhancing cucumber resistance to Podosphaera fuliginea. Sci. Hortic. 261. https://doi.org/10.1016/j.scienta.2019.108780.

Fageria, N.K., Filho, M.P.B., Moreira, A., Guimarães, C.M., 2009. Foliar fertilization of crop plants. J. Plant Nutr. 32 (6), 1044–1064. https://doi.org/10.1080/01904160902872826.

Fan, H.M., Wang, X.W., Sun, X., Li, Y.Y., Sun, X.Z., Zheng, C.S.u., 2014. Effects of humic acid derived from sediments on growth, photosynthesis and chloroplast ultrastructure in chrysanthemum. Sci. Hortic. 177, 118–123. https://doi.org/10.1016/j.scienta.2014.05.010.

FAOSTAT, 2013. Statistical database of the food and agricultural organization. Available online at http://faostat3.fao.org/home/index.html.

FAO, 2022. The State of Food Security and Nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable. FAO, Rome.

Fathima, P.S., Denesh, G.R., 2013. Influence of humic acid spray on growth and yield of chilli (*Capsicum annum* L.). International Journal of. Agric. Sci. 9 (2), 542–546.

Fathy, M.A., Gabr, M.A., el Shall, S.A., 2010. Effect of Humic Acid Treatments on "Canino" Apricot Growth, Yield and Fruit Quality. New York Sci. J. 3 (12), 109–115.

Faulin, E.J., Furquim De Azevedo, P., 2003. Distribuição de hortaliças na agricultura familiar: uma análise das transações. Informações Econômicas 22 (11), 24–37.

Felipe, L., Santoyo, R., Alcántar González, G., Ortega Escobar, M., Estrada, A.E., Soto Hernández, M., García, S., 1998. Fertilizacion foliar organica e inorganica y rendimiento de sorgo en condiciones de salinidad. Terra 16 (3).

Fernandez, V., Eichert, T., 2009. Uptake of hydrophilic solutes through plant leaves: current state of knowledge and perspectives of foliar fertilization. Crit. Rev. Plant Sci. 28 (1–2), 36–68. https://doi.org/10.1080/07352680902743069.

Fernández, V., Sotiropoulos, T., Brown, P.H., 2013. Foliar fertilization: scientific principles and field pratices. International fertilizer industry Association, Paris, pp. 1–144.

Fernández-Escobar, R., Benlloch, M., Barranco, D., Duenas, A., Gutérrez Ganán, J.A., 1996. Response of olive trees to folk application of humic substances extracted from leonardite. Sci. Hortic. 66, 191–200.

Ferrara, G., Brunetti, G., 2010. Efectos de los tiempos de aplicación de un ácido húmico del suelo sobre la calidad de las bayas de uva de mesa (Vitis vinifera L.) cv Italia. Span. J. Agric. Res. 8 (3), 817–822. https://doi.org/10.5424/1283.

Filgueiras, T.S., 2021. Gramíneas do cerrado. IBGE, Rio de Janeiro.

Fischer, T., 2017. Humic supramolecular structures have polar surfaces and unpolar cores in native soil. Chemosphere 183, 437–443. https://doi.org/10.1016/j.chemosphere.2017.05.125.

Fontaneli, R.S., Pereira, H., Santos, D., Carlos Baier, A., 2009. Morfologia de leguminosas forrageiras. In: Fontaneli, R.S., Santos, H.P.F.R.S. (Eds.), Forrageiras para Integração Lavoura-Pecuária-Floresta na Região Sul-Brasileira. 1 ed. Embrapa Trigo, Passo Fundo.

Franke, W., 1967. Mechanisms of foliar penetration of solutions. Annu. Rev. Plant Physiol. 18, 281–300.

Frioni, T., VanderWeide, J., Palliotti, A., Tombesi, S., Poni, S., Sabbatini, P., 2021. Foliar vs. soil application of Ascophyllum nodosum extracts to improve grapevine water stress tolerance. Sci. Hortic. 277. https://doi.org/10.1016/j.scienta.2020.109807.

Fu, Y., Zhong, X., Zeng, J., Liang, K., Pan, J., Xin, Y., Liu, Y., Hu, X., Peng, B., Chen, R., Hu, R., 2021. Improving grain yield, nitrogen use efficiency and radiation use efficiency by dense planting, with delayed and reduced nitrogen application, in double cropping rice in South China. J. Integr. Agric. 20 (2), 565–580. https://doi.org/10.1016/S2095-3119(20)63380-9.

García, A C, Castro, T. A. V. T., Berbara, R. L. L., Elias, S. S., Amaral Sobrinho, N. M. B., Pereira, M. G., Zonta, E. 2019. Revisão Sobre a Relação Estrutura-Função das Substâncias Húmicas e a sua Regulação do Metabolismo Oxidativo em Plantas Critical. (Retrieved on from http://rvq.sbq.org.br).

García, A.C., Santos, L.A., Izquierdo, F.G., Sperandio, M.V.L., Castro, R.N., Berbara, R.L.L., 2012. Vermicompost humic acids as an ecological pathway to protect rice plant against oxidative stress. Ecol. Eng. 47, 203–208. https://doi.org/10.1016/j.ecoleng.2012.06.011.

García, A.C., Santos, L.A., de Souza, L.G.A., Tavares, O.C.H., Zonta, E., Gomes, E.T.M., García-Mina, J.M., Berbara, R.L.L., 2016. Vermicompost humic acids modulate the accumulation and metabolism of ROS in rice plants. J. Plant Physiol. 192, 56–63. https://doi.org/10.1016/j.jplph.2016.01.008.

Gerardin, T., Douthe, C., Flexas, J., Brendel, O., 2018. Shade and drought growth conditions strongly impact dynamic responses of stomata to variations in irradiance in Nicotiana tabacum. Environ. Exp. Bot. 153, 188–197. https://doi.org/10.1016/j.envexpbot.2018.05.019.

Gerum, A.D.A., Santos, G.S., Santana, M.D.A., Souza, J.D.S., Cardoso, C.E.L., 2019. Fruticultura Tropical: potenciais riscos e seus impactos. Cruz das Almas, p. 128.

Gerzabek, M.H., Aquino, A.J.A., Balboa, Y.I.E., Galicia-Andrés, E., Grančič, P., Oostenbrink, C., Petrov, D., Tunega, D., 2022. A contribution of molecular modeling to supramolecular structures in soil organic matter. J. Plant Nutr. Soil Sci. 185 (1), 44–59. https://doi.org/10.1002/jpln.202100360.

Ghanbarpour, E., Rezaei, M., Lawson, S., 2019. Reduction of cracking in pomegranate fruit after foliar application of humic acid, calcium-boron and kaolin during water stress. Erwerbs-obstbau 61 (1), 29–37. https://doi.org/10.1007/s10341-018-0386-6.

Haider, F.U., Liqun, C., Coulter, J.A., Cheema, S.A., Wu, J., Zhang, R., Wenjun, M., Farooq, M., 2021. Cadmium toxicity in plants: Impacts and remediation strategies. Ecotoxicol. Environ. Saf. 211. https://doi.org/10.1016/j.ecoenv.2020.111887.

Hasan, A.M., 2019. Effect of foliar application of humic acid and benzyladenine on growth and flowering of pot marigold (Calendula officinalis L.). J. Univ. Duhok 22 (1), 69–77. https://doi.org/10.26682/avuod.2019.22.1.7.

Hassan, H., Fahmy, A., 2020. Effect of foliar spray with proline and humic acid on productivity and essential oil content of chamomile plant under different rates of organic fertilizers in sandy soil. J. Plant Product. 11 (1), 71–77. https://doi.org/10.21608/jpp.2020.79156.

Hatami, E., Shokouhian, A.A., Ghanbari, A.R., Naseri, L.A., 2018. Alleviating salt stress in almond rootstocks using of humic acid. Sci. Hortic. 237, 296–302. https://doi.org/10.1016/j.scienta.2018.03.034.

Hernandez, O.L., Calderín, A., Huelva, R., Martínez-Balmori, D., Guridi, F., Aguiar, N. O., Olivares, F.L., Pasqualoto Canellas, L., 2015. Humic substances from vermicompost enhance urban lettuce production. Agronomy Sustain. Dev. 35 (1). https://doi.org/10.1007/s13593.

Hernández, R., Robles, C., Calderín, A., Guridi, F., Reynaldo, I.M., González, D., 2018. Efectos anti estrés de ácidos húmicos de vermicompost en dos cultivares de arroz (*Oryza sativa* L). Cultivos Tropicales 39 (2), 65–74.

Huang, S., Wang, P., Yamaji, N., Ma, J.F., 2020. June 1Plant Nutrition for Human Nutrition: Hints from Rice Research and Future Perspectives. Mol. Plant Cell Press. https://doi.org/10.1016/j.molp.2020.05.007.

Jan, J.A., Nabi, G., Khan, M., Ahmad, S., Shah, P.S., Hussain, S., Sehrish, S., 2020. Foliar application of humic acid improves growth and yield of chilli (Capsicum annum L.) varieties. Pak. J. Agric. Res. 33 (3). https://doi.org/10.17582/journal.pjar/2020/33.3.461.472.

Jawad, R.M., Majeed, B.H., 2017. Floral characters of gerbera (Gerbera jamesonii) as affected by foliar application of humic acid and calcium chloride. Zagazig J. Agric. Res 44 (3).

Jeffree, C. E. 2007. The Fine Structure of the Plant Cuticle. In: Annual Plant Reviews. Vol. 23, pp. 11–125. Wiley Blackwell.

Jindo, K., Olivares, F.L., da Malcher, D.J., Sánchez-Monedero, M.A., Kempenaar, C., Canellas, L.P., 2020. From lab to field: role of humic substances under open-field and greenhouse conditions as biostimulant and biocontrol agent. Front. Plant Sci. Front. Media S.A. https://doi.org/10.3389/fpls.2020.00426.

Jung, H., Kwon, S., Kim, J., Jeon, J., 2021. Which traits of humic substances are investigated to improvetheir agronomical value? Molecules 26 (760), 1–10. https://doi.org/10.3390/molecules.

Kamel, S.M., Afifi, M.M.I., El-shoraky, F.S., El-Sawy, M.M., 2014. Fulvic acid: a tool for controlling powdery and downy mildews in cucumber plants. Int. J. Phytopathol. 3 (2), 101–108. https://doi.org/10.33687/phytopath.003.02.0866.

Kandil, E.E., Abdelsalam, N.R., el Aziz, A.A.A., Ali, H.M., Siddiqui, M.H., 2020. Efficacy of nanofertilizer, fulvic acid and boron fertilizer on sugar beet (Beta vulgaris L.) yield and quality. Sugar Tech 22 (5), 782–791. https://doi.org/10.1007/s12355-020-00837-8.

Kandil, A.A., Sharief, A.E., Fathalla, F.H., 2012. Onion yield as affected by foliar application with amino and humic acids under nitrogen fertilizer levels. ESci J. Crop Product. 02 (02), 62–72.

Karakurt, Y., Unlu, H., Unlu, H., Padem, H., 2009. The influence of foliar and soil fertilization of humic acid on yield and quality of pepper. Acta Agric. Scand. B. Soil Plant Sci. 59 (3), 233–237. https://doi.org/10.1080/09064710802022952.

Karakurt, Y., Ozdamar-Unlu, H., Unlu, H., Tonguc, M., 2015. Antioxidant compounds and activity in cucumber fruit in response to foliar and soil humic acid application. Eur. J. Hortic. Sci. 80 (2), 76–80. https://doi.org/10.17660/eJHS.2015/80.2.5.

Katkat, A., Çelik, H., Turan, M.A., Asýk, B.B., 2009. Effects of soil and foliar applications of humic substances on dry weight and mineral nutrients uptake of wheat under calcareous soil conditions. Aust. J. Basic Appl. Sci. 3 (2), 1266–1273.

Kaya, M., Atak, M., Khawar, M., Çiftçi, C.Y., Özcan, S., 2005. Effect of pre-sowing seed treatment with zinc and foliar spray of humic acids on yield of common bean (Phaseolus vulgaris L.). Int. J. Agric. e Biol. 7 (6), 875–878.

Kaya, C., Şenbayram, M., Akram, N.A., Ashraf, M., Alyemeni, M.N., Ahmad, P., 2020. Sulfur-enriched leonardite and humic acid soil amendments enhance tolerance to drought and phosphorus deficiency stress in maize (*Zea mays* L.). Sci. Rep. 10 (1). https://doi.org/10.1038/s41598-020-62669-6.

Kazemi, M., 2013. Effect of foliar application of humic acid and potassium nitrate on cucumber growth. Env. Pharmacol. Life Sci 2 (11), 3–06.

Khaled, H., Fawy, H.A., 2011. Effect of different levels of humic acids on the nutrient content, plant growth, and soil properties under conditions of salinity. Soil & Water Res. 6 (1), 21–29.

Khan, M.A., Asaf, S., Khan, A.L., Jan, R., Kang, S.M., Kim, K.M., Lee, I.J., 2020. Extending thermotolerance to tomato seedlings by inoculation with SA1 isolate of Bacillus cereus and comparison with exogenous humic acid application. PLoS One 15 (4). https://doi.org/10.1371/journal.pone.0232228.

Khorasaninejad, S., Alizadeh Ahmadabadi, A., Hemmati, K., 2018. The effect of humic acid on leaf morphophysiological and phytochemical properties of Echinacea purpurea L. under water deficit stress. Sci. Hortic. 239, 314–323. https://doi.org/10.1016/j.scienta.2018.03.015.

Kishor, M., Jayakumar, M., Gokavi, N., Mukharib, D.S., Raghuramulu, Y., Udayar Pillai, S., 2021. Humic acid as foliar and soil application improve the growth, yield and quality of coffee (cv. C × R) in Western Ghats of India. J. Sci. Food Agric. 101 (6), 2273–2283. https://doi.org/10.1002/jsfa.10848.

Kovalchuk, N.M., Simmons, M.J.H., 2021. Surfactant-mediated wetting and spreading: recent advances and applications. Curr. Opin. Colloid Interface Sci. 51. https://doi.org/10.1016/j.cocis.2020.07.004.

Kritzinger, I., Lötze, E., 2019. Quantification of lenticels in Japanese plum cultivars and their effect on total fruit peel permeance. Sci. Hortic. 254, 35–39. https://doi.org/10.1016/j.scienta.2019.04.082.

Leite, J.M., Pitumpe Arachchige, P.S., Ciampitti, I.A., Hettiarachchi, G.M., Maurmann, L., Trivelin, P.C.O., Prasad, P.V.V., Sunoj, S.V.J., 2020. Co-addition of humic substances and humic acids with urea enhances foliar nitrogen use efficiency in sugarcane (Saccharum officinarum L.). Heliyon 6 (10). https://doi.org/10.1016/j.heliyon.2020.e05100.

Lenssen, A.W., Olk, D.C., Dinnes, D.L., 2019. Application of a formulated humic product can increase soybean yield. Crop, Forage & Turfgrass Manage. 5, (1). https://doi.org/10.2134/cftm2018.07.0053 180053.

Leventoglu, H., Erdal, I., 2014. Effect of high humic substance levels on growth and nutrient concentration of corn under calcareous conditions. J. Plant Nutr. 37 (12), 2074–2084. https://doi.org/10.1080/01904167.2014.920373.

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, H., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., Sen, P.T., Sessa, R., Shula, R., Tibu, A., Torquebiau, E.F., 2014. Climate-smart agriculture for food security. Nature Climate Change 4, 1068–1072. https://doi.org/10.1038/nclimate2437.

Liu, A., Contador, C.A., Fan, K., Lam, H.M., 2018. Interaction and regulation of carbon, nitrogen, and phosphorus metabolisms in root nodules of legumes. Plant Sci. Front. Media S.A. https://doi.org/10.3389/fpls.2018.01860.

Lotfi, R., Pessarakli, M., Gharavi-Kouchebagh, P., Khoshvaghti, H., 2015. Physiological responses of Brassica napus to fulvic acid under water stress: Chlorophyll a fluorescence and antioxidant enzyme activity. Crop J. 3 (5), 434–439. https://doi.org/10.1016/j.cj.2015.05.006.

Mahmoudi, M., Samavat, S., Mostafavi, M., Khalighi, A., Cherati, A., 2014. The effects of humic acid and proline on morphological properties of Actindia Deliciosa cv. Hayward under salinity. J. Appl. Sci. Agric. 9 (1), 261–267.

Maibodi, N.D.H., Kafi, M., Nikbakht, A., Rejali, F., 2015. Effect of foliar applications of humic acid on growth, visual quality, nutrients content and root parameters of perennial ryegrass (Lolium Perenne L.). J. Plant Nutr. 38 (2), 224–236. https://doi.org/10.1080/01904167.2014.939759.

Manas, D., Soumya, G., Kheyali, S., 2014. Effect of humic acid application on accumulation of mineral nutrition and pungency in garlic (Allium sativum L.). Int. J. Biotechnol. Mol. Biol. Res. 5 (2), 7–12. https://doi.org/10.5897/ijbmbr2014.0186.

Man-hong, Y., Lei, Z., Sheng-tao, X., McLaughlin, N.B., 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. Sci. Rep. 10 (1). https://doi.org/10.1038/s41598-020-63925-5.

Mazhar, A.A.M., Shedeed, S.I., Abdel-Aziz, M.G., Mahgoub, M.H., 2012. Growth, flowering and chemical constituents of Chrysanthemum indicum L. Plant in response to different levels of humic acid and salinity. J. Appl. Sci. Res. 8 (7), 3697–3706.

Meena, M.K., Dhanoji, M.M., Chandra Naik, M., 2018. Influence of humic acid foliar spray on physiological growth indices in Redgram (Cajanus cajan). Pharmacology and Life Sciences Bull. Env. Pharmacol. Life Sci., 57–63

Merget, A., 1873. Sur des phenomenes de thermodiffusion gazeuse qui se produisent dans les feuilles et sur les mouvements circulatoires qui en r ´esultantdans l'acte de la respiration chlorophyllienne. Compt. Ren, Acad, Sci. 77, 1468–1472.

Mocellin, R. S. P. 2004. Princípios das adubação foliar. Canoas.

Monda, H., Cozzolino, V., Vinci, G., Drosos, M., Savy, D., Piccolo, A., 2018. Molecular composition of the Humeome extracted from different green composts and their biostimulation on early growth of maize. Plant and Soil 429 (1–2), 407–424. https://doi.org/10.1007/s11104-018-3642-5.

Monda, H., McKenna, A.M., Fountain, R., Lamar, R.T., 2021. Bioactivity of Humic Acids Extracted From Shale Ore: Molecular Characterization and Structure-Activity Relationship With Tomato Plant Yield Under Nutritional Stress. Front. Plant Sci. 12. https://doi.org/10.3389/fpls.2021.660224.

Muscolo, A., Sidari, M., Nardi, S., 2013. Humic substance: Relationship between structure and activity. deeper information suggests univocal findings. J. Geochem. Explor. 129, 57–63. https://doi.org/10.1016/j.gexplo.2012.10.012.

Nachtiqaü, G.R., Nava, G., 2010. Adubação foliar: Fatos e mitos. Agropecuária Catarinense 23 (2), 87–97.

Najarian, A., Souri, M.K., Nabigol, A., 2022. Influence of humic substance on vegetative growth, flowering and leaf mineral elements of Pelargonium x hortorum. J. Plant Nutr. 45 (1), 107–112.

Nardi, S., Panuccio, M.R., Abenavoli, M.R., Muscolo, A., 1994. Auxin-like effect of humic substances extracted from faeces of Allolobophora caliginosa and A. Rosea. Soil Eiol. Biochem 26 (IO), 1341–1346.

Nardi, S., Concheri, G., Pizzeghello, D., Sturaro, A., Rella, R., Parvoli, G., 2000a. Soil organic matter mobilization by root exudates. Chemosphere 41, 653–658.

Nardi, S., Pizzeghello, D., Reniero, F., Rascio, N., 2000b. Chemical and biochemical properties of humic substances isolated from forest soils and plant growth. Soil Sci. Soc. Am. J. 64 (2), 639–645. https://doi.org/10.2136/sssaj2000.642639x.

Nardi, S., Pizzeghello, D., Ertani, A., 2018. Hormone-like activity of the soil organic matter. Appl. Soil Ecol. 123, 517–520. https://doi.org/10.1016/j.apsoil.2017.04.020.

Nardi, S., Schiavon, M., Francioso, O., 2021. Chemical structure and biological activity of humic substances define their role as plant growth promoters. MoleculesMDPI AG. https://doi.org/10.3390/molecules26082256.

Nebbioso, A., Piccolo, A., Lamshöft, M., Spiteller, M., 2014. Molecular characterization of an end-residue of humeomics applied to a soil humic acid. RSC Adv. 4 (45), 23658–23665. https://doi.org/10.1039/c4ra01619j.

Ngullie, C.R., Tank, R.V., Bhanderi, D.R., 2014. Effect of salicylic acid and humic acid on flowering, fruiting, yield and quality of mango (Mangifera indica L.) cv. Kesar. Adv. Res. J. Crop Improvement 5 (2), 136–139. https://doi.org/10.15740/has/arjci/5.2/136-139.

O'Donnell, R.W., 1972. The auxin-like effects of humic preparations from leonardite. Soil Sci. 116 (2), 106–112.

Olaetxea, M., de Hita, D., Garcia, C.A., Fuentes, M., Baigorri, R., Mora, V., Garnica, M., Urrutia, O., Erro, J., Zamarreño, A.M., Berbara, R.L., Garcia-Mina, J.M., 2018. Hypothetical framework integrating the main mechanisms involved in the promoting action of rhizospheric humic substances on plant root- and shoot-growth. Appl. Soil Ecol. 123, 521–537. https://doi.org/10.1016/j.apsoil.2017.06.007.

Olaetxea, M., Mora, V., Bacaicoa, E., Baigorri, R., Garnica, M., Fuentes, M., Zamarreño, A.M., Spíchal, L., García-Mina, J.M., 2019. Root ABA and H+-ATPase are key players in the root and shoot growth-promoting action of humic acids. Plant Direct 3 (10). https://doi.org/10.1002/pld3.175.

Olivares, F.L., Aguiar, N.O., Rosa, R.C.C., Canellas, L.P., 2015. Substrate biofortification in combination with foliar sprays of plant growth promoting bacteria and humic substances boosts production of organic tomatoes. Sci. Hortic. 183 (1), 100–108. https://doi.org/10.1016/j.scienta.2014.11.012.

Oliveira Amatussi, J., Francisco Mógor, Á., Mógor, G., Bochetti de Lara, G., 2020. Novel use of calcareous algae as a plant biostimulant. J. Appl. Phycol. 32, 2023–2030. https://doi.org/10.1007/s10811-020-02077-5/Published.

Olk, D.C., Dinnes, D.L., Rene Scoresby, J., Callaway, C.R., Darlington, J.W., 2018. Humic products in agriculture: potential benefits and research challenges—a review. J. Soil. Sediment. 18 (8), 2881–2891. https://doi.org/10.1007/s11368-018-1916-4.

Osman, E.A.M., El-Masry, A.A., Khatab, K.A., 2013. Effect of nitrogen fertilizer sources and foliar spray of humic and/or fulvic acids on yield and quality of rice plants. Pelagia Res. Library Adv. Appl. Sci. Res. 4 (4), 174–183.

Osvalde, A., Karlsons, A., Čekstere, G., Maļecka, S. 2013. Effect of humic substances on nutrient status and yield of Onion (Allium Cepa L.) in field conditions. In: Proceedings of the Latvian Academy of Sciences. Section B. Natural, Exact, and Applied Sciences, 66(4–5), 192–199. doi: 10.2478/v10046-012-0028-6.

Ozfidan-Konakci, C., Yildiztugay, E., Bahtiyar, M., Kucukoduk, M., 2018. The humic acid-induced changes in the water status, chlorophyll fluorescence and antioxidant defense systems of wheat leaves with cadmium stress. Ecotoxicol. Environ. Saf. 155, 66–75. https://doi.org/10.1016/j.ecoenv.2018.02.071.

Perminova, I., García-Mina, J.M., Knicker, H., Miano, T., 2019. Humic substances and nature-like technologies: Learning from nature: understanding humic substances structures and interactions for the development of environmentally friendly, nature-like technologies. J. Soil. Sediment. 19 (6), 2663–2664. https://doi.org/10.1007/s11368-019-02330-6.

Piccolo, A., 2002. The supramolecular structure of humic substances: A novel understanding of humus chemistry and implications in soil science. Adv. Agron. 75, 57–134. https://doi.org/10.1016/s0065-2113(02)75003-7.

Pittarello, M., Busato, J.G., Carletti, P., Zanetti, L.V., da Silva, J., Dobbss, L.B., 2018. Effects of different humic substances concentrations on root anatomy and Cd accumulation in seedlings of Avicennia germinans (black mangrove). Mar. Pollut. Bull. 130, 113–122. https://doi.org/10.1016/j.marpolbul.2018.03.005.

Pizzeghello, D., Nicolini, G., Nardi, S., 2002. Hormone-like activities of humic substances in different forest ecosystems. New Phytol. 155 (3), 393–402. https://doi.org/10.1046/j.1469-8137.2002.00475.x.

Pizzeghello, D., Francioso, O., Ertani, A., Muscolo, A., Nardi, S., 2013. Isopentenyladenosine and cytokinin-like activity of different humic substances. J. Geochem. Explor. 129, 70–75. https://doi.org/10.1016/j.gexplo.2012.10.007.

Pizzeghello, D., Schiavon, M., Francioso, O., Dalla Vecchia, F., Ertani, A., Nardi, S., 2020. Bioactivity of size-fractionated and unfractionated humic substances from two forest soils and comparative effects on n and s metabolism, nutrition, and root anatomy of Allium sativum L. Front. Plant Sci. 11. https://doi.org/10.3389/fpls.2020.01203.

Popescu, G.C., Popescu, M., 2018. Yield, berry quality and physiological response of grapevine to foliar humic acid application. Bragantia 77 (2), 273–282. https://doi.org/10.1590/1678-4499.2017030.

Portu, J., González-Arenzana, L., Hermosín-Gutiérrez, I., Santamaría, P., Garde-Cerdán, T., 2015. Phenylalanine and urea foliar applications to grapevine: effect on wine phenolic content. Food Chem. 180, 55–63. https://doi.org/10.1016/j.foodchem.2015.02.008.

Qiu, C., Sun, J., Shen, J., Zhang, S., Ding, Y., Gai, Z., Fan, K., Song, L., Chen, B., Ding, Z., Wang, Y., 2021. Fulvic acid enhances drought resistance in tea plants by regulating the starch and sucrose metabolism and certain secondary metabolism. J. Proteomics 247. https://doi.org/10.1016/j.jprot.2021.104337.

Rachid, A.F., Rahem Bader, B., 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 Arch. 20, 32–37.

Raheem, S., Ibrahum Al-Jaf, H., Raheem, S.M., Al-Jaf, H.I., Tofiq, G.K., 2018. Influence of foliar and soil application of humic acid on growth and yield of lettuce. Euphrates J. Agric. Sci. 10 (2), 199–204.

Razavi Nasab, A., Fotovat, A., Astaraie, A., Tajabadipour, A., 2019. Effect of Organic Waste and Humic Acid on Some Growth Parameters and Nutrient Concentration of Pistachio Seedlings. Commun. Soil Sci. Plant Anal. 50 (3), 254–264. https://doi.org/10.1080/00103624.2018.1559328.

Reddy, K. ., Bhuvaneswari, R., Karthikeyan, P.K. 2020. Effect of dap, humic acid and micronutrient mixture foliar application on yield and quality characters of groundnut (Arachis hypogaea l.) Var. Tmv 7 in sandy loam soil. Vol. 20 p. 521–525.

Reyes Perez, J.J., Izquierdo, F.G., Escobar, I.M.R., Ortega, Y.R., Mayoral, J.A.L., Amador, B.M., Espinoza, F.H.R., Fabre, T.B., Amador, C.A., Silvera, C.M.O., Morales, Y.A., Milanés, J.Y.R., 2011. Efectos del humus líquido sobre algunos parámetros decalidad interna en frutos de tomate cultivados encondiciones de estrés salino. Centro Agricola 38 (3), 57–61.

Ribeiro, F.E., del Peloso, M.J., Barbosa, F.R., de Gonzaga, A.C., de Oliveira, L.F.C., 2011. Recomendações técnicas para o cultivo do feijoeiro-comum (*Phaseolus vulgaris* L.) nas regiões Norte e Nordeste do Brasil. Circular técnica 89, 1–64.

Rodrigues, E.S., Montanha, G.S., Marques, J.P.R., de Almeida, E., Yabuki, L.N.M., Menegário, A.A., Pereira de Carvalho, H.W., 2020. Foliar application of rare earth elements on soybean (*Glycine max* (L)): Effects on biometrics and characterization of phytotoxicity. J. Rare Earths 38 (10), 1131–1139. https://doi.org/10.1016/j.jre.2019.09.004.

Rodrigues, L.U., Ribeiro Da Silva, R., Araújo De Freitas, G., Carlos, A., dos Santos, M., De, R., Tavares, C., 2018. Applied Research & Agrotechnology vol 11, n.2, may/aug. https://doi.org/10.5935/PAeT.V11.N2.11.

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

Sachs, J., 1884. Ein Beitrag zur Kenntniss der Ern ¨ahrungsth ¨atigkeit der Bl ¨atter. Arbeit. Botan. Inst. W ¨urzburg 3, 1–33.

Safaei, Z., Azizi, M., Davarynejad, G., Aroiee, H., 2014. The Effect of Foliar Application of Humic Acid and Nanofertilizer (Pharmks $^{®}$) on Yield and Yield Components of Black Cumin (Nigella sativa L.). J. Medicinal Plants By-products. 2, 133–140.

Saidimoradi, D., Ghaderi, N., Javadi, T., 2019. Salinity stress mitigation by humic acid application in strawberry (Fragaria x ananassa Duch.). Sci. Hortic. 256. https://doi.org/10.1016/j.scienta.2019.108594.

Sant'Anna, S.A.C., Martins, M.R., Goulart, J.M., Araújo, S.N., Araújo, E.S., Zaman, M., Jantalia, C.P., Alves, B.J.R., Boddey, R.M., Urquiaga, S., 2018. Biological nitrogen fixation and soil N_2O emissions from legume residues in an Acrisol in SE Brazil. Geoderma Reg. 15. https://doi.org/10.1016/j.geodrs.2018.e00196.

Santoyo, L.F.R., González, G.A., Escobar, M.O., Estrada, A.E., Hernández, M.S., García, P.S., 1998. Fertilizacion foliar organica e inorganica y rendimiento de sorgo en condiciones de salinidad. Terra 16 (3), 205–210.

Savy, D., Brostaux, Y., Cozzolino, V., Delaplace, P., du Jardin, P., Piccolo, A., 2020. Quantitative structure-activity relationship of humic-like biostimulants derived from agro-industrial byproducts and energy crops. Front. Plant Sci. 11. https://doi.org/10.3389/fpls.2020.00581.

Schreel, J.D.M., Steppe, K., 2020. Foliar water uptake in trees: negligible or necessary? Trends Plant Sci. 25 (6), 590–603. https://doi.org/10.1016/j.tplants.2020.01.003.

Shahabivand, S., Padash, A., Aghaee, A., Nasiri, Y., Rezaei, P.F., 2018. Plant biostimulants (Funneliformis mosseae and humic substances) rather than chemical fertilizer improved biochemical responses in peppermint. Iranian J. Plant Physiol. 8 (2), 2333–2344. https://doi.org/10.22034/ijpp.2018.539109.

Shindhe, V., Dhanoji, M.M., Meena, M.K., Patil, R.P., 2020. Influence of foliar organic nutrition on growth, yield and yield components of sunflower. J. Pharmacognosy Phytochem. 9 (1), 1267–1269.

Silva-Matos, R.R.S., Cavalcante, Í.H.L., Júnior, G.B.S., Albano, F.G., Cunha, M.S., Beckmann-Cavalcante, M.Z., 2012. Foliar spray of humic substances on seedling production of watermelon cv. Crinson sweet. J. Agron. 11 (2), 60–64.

Sindha, D.J., Satodiya, B.N., Sutariya, N.K., 2018. Effect of foliar application of different chemicals and humic acid on fruit yield and quality of custard apple (Annona squamosa L.) cv local. Int. J. Chem. Stud. 6 (5), 75–77.

Sladky, Z., 1959. The application of extracted humus substances to overground parts of plants. Biol. Plant. 1 (3), 199–204.

Souri, M.K., Hatamian, M., 2019. Aminochelates in plant nutrition: a review. J. Plant Nutr. 42 (1), 67–78.

Stevenson, F.J., 1994. Humus chemistry. Genesis, composition, reactions. John Wileyand Sons, New York.

Suh, H.Y., Yoo, K.S., Suh, S.G., 2014. Tuber growth and quality of potato (Solanum tuberosum L.) as affected by foliar or soil application of fulvic and humic acids. Hortic. Environ. Biotechnol. 55 (3), 183–189. https://doi.org/10.1007/s13580-014-0005-x.

Susithra, M., Balasubramanian, A., Gobi, R., Sathiyamurthi, S., 2019. Yield maximization with nutrient management and nursery practices on transplanted red gram (Cajanus cajan (L) MILLSP.). Plants Arch. 19 (1), 323–326.

Tagliavini, M., Toselli, M., 2005. Foliar applications of nutrients. Food-Web Interactions, 53–59.

Tavares, O.C.H., Santos, L.A., Ferreira, L.M., Sperandio, M.V.L., Da Rocha, J.G., García, A.C., Dobbss, L.B., Berbara, R.L.L., De Souza, S.R., Fernandes, M.S., 2017. Humic acid differentially improves nitrate kinetics under low- and high-affinity systems and alters the expression of plasma membrane H + -ATPases and nitrate transporters in rice. Annals of Applied Biology 170, 89–103. https://doi.org/10.1111/aab.12317.

Tei, F., de Neve, S., de Haan, J., Kristensen, H.L., 2020. Nitrogen management of vegetable crops. Agric. Water Manage. 240. https://doi.org/10.1016/j.agwat.2020.106316.

Tejada, M., Gonzalez, J.L., 2003. Influence of foliar fertilization with amino acids and humic acids on productivity and quality of asparagus. Biol. Agric. Hortic. 21 (3), 277–291. https://doi.org/10.1080/01448765.2003.9755270.

Tejada, M., Rodríguez-Morgado, B., Paneque, P., Parrado, J., 2018. Effects of foliar fertilization of a biostimulant obtained from chicken feathers on maize yield. Eur. J. Agron. 96, 54–59. https://doi.org/10.1016/j.eja.2018.03.003.

Teli, S.B., Matiwade, P., Yenagi, B., Kuligod, V., 2020. Soil and foliar application of humic acid on productivity of groundnut (Arachis hypogea L.). Int. J. Chemical Stud. 8 (1), 1315–1318. https://doi.org/10.22271/chemi.2020.v8.i1r.8438.

Terra, S.B., Oliveira, D.P.P., 2013. Floricultura: a produção de flores como uma nova alternativa de emprego e renda para a comunidade de Bagé-RS. Revista Conexão UEPG 9 (2), 342–353.

Thakur, H., Rekka, K.B., Giri, Y.Y., Babu, S.N.S., Padmaja, G., 2017. Physico-Chemical Properties And Microbial Count Of Soil After Harvest Of Sunflower (Helianthus Annuus L.) As Influenced By Humic Acid And Fulvic Acid. Bull. Environ. Pharmacol. Life Sci. 6 (3), 413–416.

Tranvik, L.J., 2014. Dystrophy in Freshwater Systems☆. Reference Module in Earth Systems and Environmental Sciences. Elsevier.

Urrutia, O., Fuentes, M., Olaetxea, M., Garnica, M., Baigorri, R., Zamarreño, A. M., Movila, M., de Hita, D., Garcia-Mina, J. M. 2020. The effect of soil organic matter on plant mineral nutrition. In: Z. Rengel (Ed.), Achieving sustainable crop nutrition. pp. 291–306.

Vaccaro, S., Ertani, A., Nebbioso, A., Muscolo, A., Quaggiotti, S., Piccolo, A., Nardi, S., 2015. Humic substances stimulate maize nitrogen assimilation and amino acid metabolism at physiological and molecular level. Chem. Biol. Technol. Agric. 2 (1). https://doi.org/10.1186/s40538-015-0033-5.

van Tol de Castro, T.A., García, A.C., Tavares, O.C.H., Pereira, E.G., de Souza, C.D.C.B., Torchia, D.F.D.O., de Pinho, C.F., Castro, R.N., 2022. Humic acids affect photosynthetic quantum efficiency in rice under water deficit. Theor. Exp. Plant Physiol. https://doi.org/10.1007/s40626-022-00258-w.

van Wissenlingh, C., 1895. Sur la cuticularisation et la cutine. Neerlad. Sc.Exact. Natur. 28, 373–410.

Vani, K., Rekha, B., Divya, G., Vani, K.P., Rekha, K.B., Divya, G., Nalini, N., 2017. Organic farming in Groundnut View project Quality parameters of nutri-cereal browntop millet through agronomic practices View project Performance of summer sesamum (Sesamum indicum L.) under integrated nutrient management. J. Pharmacognosy Phytochem. 6 (5).

Varanini, Z., Pinton, R., 1995. Humic Substances and Plant Nutrition. Progress in Botany, 97–117.

Villegas-Espinoza, J.A., Reyes-Pérez, J.J., Nieto-Garibay, A., Higinio Ruiz-Espinoza, F., Cruz-Falcón, A., Murillo-Amador, B., 2018. Biostimulant Liplant ® : its effect on Solanum lycopersicum (L.) grown on slightly saline soils. Revista Mexicana de Ciencias Agrícolas Special 20, 4137–4147.

von Dohl, 1947. Untersuchung der frage: bildet die cellulose die grunglage sammtlicher vegetabilixchen membranen? Bot Zeitung 5, 497–505.

Wadas, W., Dziugieł, T., 2020. Changes in assimilation area and chlorophyll content of very early potato (Solanum tuberosum L.) cultivars as influenced by biostimulants. Agronomy 10 (3). https://doi.org/10.3390/agronomy10030387.

Wang, S., Tian, X., Liu, Q., 2020. The effectiveness of foliar applications of zinc and biostimulants to increase zinc concentration and bioavailability of wheat grain. Agronomy 10 (2). https://doi.org/10.3390/agronomy10020178.

Wang, Y., Yang, R., Zheng, J., Shen, Z., Xu, X., 2019. Exogenous foliar application of fulvic acid alleviate cadmium toxicity in lettuce (Lactuca sativa L.). Ecotoxicol. Environ. Saf. 167, 10–19. https://doi.org/10.1016/j.ecoenv.2018.08.064.

Xudan, X., 1986. The effect of foliar application of fulvic acid on water use, nutrient uptake and yield in wheat. Aust. J. Agr. Res. 37 (4), 343–350. https://doi.org/10.1071/AR9860343.

Yadav, G., Meena, M., 2021. Bioprospecting of endophytes in medicinal plants of Thar Desert: an attractive resource for biopharmaceuticals. Biotechnol. Rep, 30. https://doi.org/10.1016/j.btre.2021.e00629.

Yildirim, E., Ekinci, M., Turan, M., Ağar, G., Dursun, A., Kul, R., Alim, Z., Argin, S., 2021. Humic + Fulvic acid mitigated Cd adverse effects on plant growth, physiology and biochemical properties of garden cress. Sci. Rep. 11 (1). https://doi.org/10.1038/s41598-021-94860-8.

Yu, X., Yang, J., Wang, E., Li, B., Yuan, H., 2015. Effects of growth stage and fulvic acid on the diversity and dynamics of endophytic bacterial community in stevia rebaudiana bertoni leaves. Front. Microbiol. 6 (AUG). https://doi.org/10.3389/fmicb.2015.00867.

Zafar, S., Li, Y.L., Li, N.N., Zhu, K.M., Tan, X.L., 2019. Recent advances in enhancement of oil content in oilseed crops. J. Biotechnol. 301, 35–44. https://doi.org/10.1016/j.jbiotec.2019.05.307.

Zandonadi, D.B., Canellas, L.P., Façanha, A.R., 2007. Indolacetic and humic acids induce lateral root development through a concerted plasmalemma and tonoplast H^+ pumps activation. Planta 225, 1583–1595.

Zandonadi, D.B., Santos, M.P., Dobbss, L.B., Olivares, F.L., Canellas, L.P., Binzel, M.L., Okorokova-Façanha, A.L., Façanha, A.R., 2010. Nitric oxide mediates humic acids-induced root development and plasma membrane H^+-ATPase activation. Planta 231 (5), 1025–1036. https://doi.org/10.1007/s00425-010-1106-0.

Zandonadi, D.B., Santos, M.P.S., Medici, L.O., Silva, J., 2014. Ação da matéria orgânica e suas frações sobre a fisiologia de hortaliças. Hortic. Bras. 32, 14–20.

Zanin, S., Lidron, E., Rizzuto, R., Pallafacchina, G. 2019. Methods to measure intracellular Ca^{2+} concentration using Ca^{2+}-sensitive dyes. In: Methods in Molecular Biology. Vol. 1925, pp. 43–58. Humana Press Inc.

Zárate, N.A.H., Vieira, M.C., 2017. Hortas: conhecimentos básicos. Siriema:, Dourados: MS, pp. 1–289.

Zhou, J., Zhang, C., Du, B., Cui, H., Fan, X., Zhou, D., Zhou, J., 2021. Soil and foliar applications of silicon and selenium effects on cadmium accumulation and plant growth by modulation of antioxidant system and Cd translocation: comparison of soft vs. durum wheat varieties. J. Hazard. Mater. 402. https://doi.org/10.1016/j.jhazmat.2020.123546.

Zotarelli, L., Zatorre, N.P., Boddey, R.M., Urquiaga, S., Jantalia, C.P., Franchini, J.C., Alves, B.J.R., 2012. Influence of no-tillage and frequency of a green manure legume in crop rotations for balancing N outputs and preserving soil organic C stocks. Field Crop Res 132, 185–195. https://doi.org/10.1016/j.fcr.2011.12.013.