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Bushra Mahmoud Alwan
College of Agricultural Engineering, University of Baghdad, Iraq

Wejdan Taleb Khadim
College of Agricultural Engineering, University of Baghdad, Iraq

Naddin Aziz Salman
College of Agricultural Engineering, University of Baghdad, Iraq

Corresponding Author:
Bushra Mahmoud Alwan
College of Agricultural Engineering, University of Baghdad, Iraq

Humic acid fertilizers: Mechanistic contributions and applications in sustainable agroecosystems

Bushra Mahmoud Alwan, Wejdan Taleb Khadim and Naddin Aziz Salman

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Abstract
Humic acid fertilizers are microbial products of organic residues that are critical in supporting sustainable agroecosystems in terms of boosting agricultural soil fertility and crop production and reducing degradation of the environment. This review explains their complex functions in enhancing soil physicochemical and biological properties, increasing nutrient bioavailability, enhancing plant resistance to abiotic stresses, and reducing the use of synthetic fertilizer. It can be used as soil amendments, foliar sprays, seed priming, fertigation and rehabilitation of degraded soils and has already proven to be active in a variety of crops and agroecological situations. Nevertheless, with the obstacles that include compositional variability and economic constraints, the development of formulation and precision agriculture technologies will enhance their value, and humic acid fertilizers will be a staple of agricultural paradigms that would survive climate changes.

Keywords: Humic acid, sustainable agroecosystems, soil

Introduction

Sustainable agriculture has been a world threat as the degradation of soil, loss of nutrients and climatic changes occur. An effective method of enhancing the operations of soil and crop resilience and environmental externalities reduction is the humic acid fertilizers, which is formed via the microbial transformation of organic mediums (Canellas *et al.*, 2015) [5]. Humic acids are the key components of humus, which possess a number of unique physicochemical properties to resolve the nutrient. (Rose *et al.*, 2014) [25]. This review outlines the mechanism principles of humic acids based fertilizers and their various uses in promoting sustainable agroecosystems. Nature and Composition of Humic Humic acid is high-molecular-weight heterogeneous Sustainable agriculture has been facing the threat of degradation of soil, loss of nutrients and climatic change in the world. Another good option of enhancing the performance of soil and crop tolerance and mitigating environmental externalities is the humic acid fertilizers generated upon the microbial processing of organic materials (Canellas *et al.*, 2015) [5]. Humic acids being a key constituent of humus possess a few unique physicochemical traits correcting nutrient inefficiencies and abiotic stressors, which are compatible with regenerative agricultural principles (Rose *et al.*, 2014) [25]. The review reports the principle of mechanisms of humic acids based fertilizers and their numerous applications in enhancing sustainable agroecosystems. Nature and Composition of Humic Acid acid are heterogeneous organic macromolecules of high-molecular weight which are formed during the decomposition of plant and animal remains within soils, peat or leonhardite. It is a carboxyl, hydroxyl and phenolic functional group aromatic and aliphatic compound and it enhances interactions between humic acid and soil nutrients, water and communities of microbes (Pettit, 2012) [22]. It is mined in leonhardites or peat and refined into powders, granules or liquid concentrates and it is soluble in alkaline circumstances and insoluble in acidic circumstances making it differentiable among fulvic acid. (Canellas & Olivares, 2014) [4]. These characteristics are the foundation of its usefulness in soil fertility enhancement and plant resistance and it has become a versatile resource in modern production. us organic macromolecules are products of the microbial decomposition of plant and animal remains in soils, peat or leonhardite. It is a carboxyl, hydroxyl, and phenolic, aromatic and aliphatic compound that facilitates interactions between humic acid and soil nutrients, water, and microbes communities (Pettit, 2012) [22]. It is mined in leonhardite or peat and prepared into powders, granules or liquid concentrates and soluble in alkaline conditions and insoluble in acid conditions which characterizes it apart in fulvic acid. (Canellas & Olivares, 2014) [4]. These attributes are the foundations of its efficacy in assisting to increase the soil fertility and the resistance of plants hence its usefulness as a versatile tool in modern farming (Seyedbagheri, 2010) [27]. Humic Acid Fertilizers in Agriculture Significance Humic acid fertilizers can exert an overall extreme effect on agronomic productivity because of improving the Soil physical architecture. The humic acid fertilizer provides stability of the aggregates by binding mineral particles thus enhancing porosity and aeration which become indispensable when it comes to growth in roots and microbes (Piccolo, 2012) [23]. Humic acid promotes the water retention due to the hydrated complex formed in the sandy soils and reduction of the losses of water due to evaporation and leaching in the drylands. (Zhang *et al.*, 2017) [34]. It also reduces compaction and therefore bulk density in soils that have high clay content and therefore the roots can easily penetrate (Jindo *et al.*, 2012) [11]. Such modifications promote resilient soil matrices, particularly in eroded landscapes, which are able to support the sustainable land management (Ouni *et al.*, 2014) [20]. Optimization of Soil Chemical Dynamics Humic acid fertilizers can form chelates with both macronutrients (e.g., nitrogen, phosphorus, potassium) and micronutrients (e.g., iron, zinc) and mitigate the loss of leaching to the high-precipitation area (Garcia *et al.*, 2016 [35] This che Further, humic acid is able to manage the pH of soil by making alkaline soils less toxic to aluminum, and making micronutrients more dissolvable in alkaline soils (Tahiri *et al.*, 2016) [28]. It also enhances cation exchange capacity that also maximizes nutrient retention that reduces nutrient loss into the environment (Yang *et al.*, 2019) [32]. Stimulation of Soil Microbial Ecosystems Humic acid fertilizers would stimulate Soil microbial activity that serves as a source of carbon as well as to provide the optimal edaphic conditions. They activate bacterial, fungal, and actinomycetes populations, which lead to the decomposition of organic matter and nutrient cycles (Puglisi *et al.*, 2013) [24]. The fixation of nitrogen and the dissolution of the phosphate are increased, and thus, this improves the fertility of soil without artificial fertilizer. (Nardi *et al.*, 2020) [18]. Field experiments reveal that humic acid application improves microbial biomass by 30 percent, which limits the yield of crops (Canellas *et al.*, 2020) [6]. Plant Abiotic Stress Amelioration of abiotic stresses caused by drought, salinity, heavy metal toxicity, and so on limits crop yield. Humic acid increases the endurance of plants as it increases water-use-efficiency, stabilizes osmotic gradient, and soaks up unhealthy ions (Kulikova *et al.*, 2016) [15]. It stabilizes heavy metals thereby lowering their bioavailability (Perminova *et al.*, 2012) [21], and causes the expression of stress-responsive proteins and antioxidants, strengthening plant defenses (Trevisan *et al.*, 2010) [29]. Hemic acid fertilizers help reduce environmental effects like eutrophication and acidification of soils by increasing nutrient-use efficiency and decreasing the synthetic fertilizer inputs (Rose *et al.*, 2014) [25]. Humic acid fertilizers are important in maintaining yields in the climatically challenged environments (Lal, 2015) [16]. Humic Acid Fertilizers are used in a wide range of modalities, according to the specifics of crops and soils:

Soil Incorporation: Granular or powdered types improve the microbial activity and the soil structure and studies have shown 10-20 percent yield increase in cereals (Jindo *et al.*, 2016) [12].

Foliar Application: Sprays make direct nutrient absorption to enhance photosynthesis and quality of fruits in horticultural crops (Canellas *et al.*, 2015) [5].

Seed Priming: There is an improvement in seed germination and seedling vigor using humic acid treatment, especially legumes (Zandonadi *et al.*, 2010) [33].

Fertigation: Liquid formulations help in proper delivery of nutrients in an irrigated system (Verlinden *et al.*, 2010) [30].

Soil Rehabilitation: Applications regenerate the eroded or salty soils (Khaled & Fawy, 2011) [13].

Synergy with Fertilizers: Humic acid supplements the effect of other fertilizers, decreases the cost of inputs. (García *et al.*, 2016) [9].

Case Studies and Empirical DataHumic acid effectiveness is proven by empirical research. The improvement of nutrient uptake led to an increase in the rice yield in Southeast Asia by 15% (Canellas & Olivares, 2014) [4]. Foliar applications in Mediterranean vineyards led to better quality of grapes (Fernandez *et al.*, 2013) [36]. In sub-Saharan Africa, degraded soils were reprimanded by the humic acid, which strengthened the productivity of smallholders (Lal, 2015) [16]. Challenges and Considerations. The humic acid varied in terms of composition, and therefore it had to be highly standardized in terms of quality (Pettit, 2012) [22]. Smallholder farmers are constrained by economic barriers (Rose *et al.*, 2014) [25]. The threat of over-application lies in the fact that it is a risk to diminishing returns and thus, it must have definite guidelines (Seyedbagheri, 2010) [27]. Future Prospects Research Future Research Future Researches Future The production of humic acid preparations that are even more specific to other agroecosystems will be a result of biotechnological development (Canellas *et al.*, 2020) [6]. It will be combined with accuracy agriculture tools such as soil sensors to make the applications as efficient as possible (Lal, 2020) [17]. Fertilizers made out of humic acid will be of high importance when the world population grows in need of food hence necessitating sustainability in intensification.. (Rose *et al.*, 2021) [26].

Conclusions

Fertilization with Humic Acid: Humic acid fertilizers have additives that enhance physical usefulness and prolong chemical nutrients preservation and microbial activity and promote optimum plant growth and sustainable health of the soil (Canellas *et al.*, 2015; Piccolo, 2012) [5, 23].

Nutrient Bioavailability: They can chelate various macronutrients and micronutrients, decrease leaching and improve plant absorption, and raise crop yields (Garcia *et al.*, 2016; Khan *et al.*, 2019) [14, 35].

Stress Resistance: Humic acid enhances the drought, salinity, and heavy metal toxicity resistance of plants, facilitates a high degree of water-use efficiency and causes stress-responsive processes (Kulikova *et al.*, 2016; Trevisan *et al.*, 2010) [15, 29].

Sustainable Practices: Humic acid fertilizers can be sustainable because of their capacity to minimize the application of synthetic fertilizers and the amount of nutrient runoffs, which is the characteristic of the regenerative agriculture, and causes the ecological sustainability. (Lal, 2020; Rose *et al.*, 2014) [17, 25].

Flexibility in different crops and agroecological conditions Since the compound can be used in different ways (foliar sprays, soil incorporation, seed priming, fertigation, and soil rehabilitation) this allows flexibility in its application. (Fernandez *et al.*, 2013; Pettit, 2012) [22, 36].

Adoption Issues: Compositional heterogeneity, and issues around cost, as well as the requirement to have accurate application protocols, requires additional research and standardization (Pettit, 2012; Seyedbagheri, 2010) [22, 27].

Future Innovations: Biotechnological and precision agriculture development will improve the efficacy of humic acid, which will be used to support the sustainable intensification that would address the global food demands. (Canellas *et al.*, 2020; Rose *et al.*, 2021) [6, 26].

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