Humic Acid: The "Black Gold" of Horticulture – A Review of Characteristics, Mechanisms and Agronomic Applications

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Abstract: Humic substances (HS), particularly humic acids (HA), have emerged as critical components in sustainable agriculture, often referred to as "Black Gold" due to their profound impact on soil health and crop productivity. This review examines the formation, classification, and physicochemical properties of humic acids. Furthermore, it synthesizes recent experimental data covering fruit crops (pear, lemon, guava, lime), berries (strawberry), and stone fruit seeds (apricot) to evaluate the efficacy of HA in enhancing yield, physiological attributes, and abiotic stress tolerance.

1. Introduction

Humic substances are ubiquitous, complex organic macromolecules found in soils, sediments, water bodies, and geological deposits. They represent the stable remains of decomposed plant and animal materials, such as lignin, tannins, cellulose, and cutins, following the process of humification.

Commercially, the primary sources of HA include coal, lignite (leonardite), and organic manures. As the agricultural sector seeks to reduce reliance on synthetic fertilizers, HA is gaining prominence for its role in optimizing nutrient use efficiency and improving soil health.

2. Classification and Chemical Characterization

Humic substances are fractionated based on their solubility in acidic and alkaline solutions into three distinct categories (Stevenson, 1994):

- **Fulvic Acid:** Characterized by the lowest molecular weight and a light yellow to brownish color. It is soluble in both acidic and alkaline environments.
- **Humic Acid:** Possesses a medium molecular weight and a dark brown color. It is soluble in alkaline solutions but precipitates (is insoluble) in acidic conditions ($pH < 2$).
- **Humin:** The fraction with the highest molecular weight and darkest (black) color. It remains insoluble in both acidic and alkali solutions.

Chemically, HA is a mixture of natural organic macromolecules containing labile protons and functional groups such as carboxylic acids, phenols, and amines. These groups are responsible for the chelating capacity of HA, allowing it to bind protons and metal ions, thereby regulating nutrient transport (Ampong et al., 2022).

3. Mechanisms of Action

The agronomic benefits of HA are derived from its influence on soil properties and plant physiology.

3.1 Soil Physical and Chemical Improvements

HA acts as a conditioner that improves soil structure and texture, leading to increased water-holding capacity (WHC). The hydrophilic nature of HA and its ability to form colloidal complexes with clay particles contribute to this retention. Additionally, HA increases the Cation Exchange Capacity (CEC) of soil, which aids in nutrient retention and prevents leaching (Billingham, 2012). It also plays a role in buffering soil pH, although its ability to alter pH depends heavily on the concentration of carboxylic and phenolic groups.

3.2 Biological and Physiological Stimulation

Biologically, HA stimulates microbial activity, providing a food source for fungi and beneficial bacteria. Physiologically, HA exhibits hormone-like activity (auxin and cytokinin), which stimulates root growth, enhances cell division, and improves stress resistance (Nardi et al., 2002). It facilitates the chelation of micronutrients, particularly iron, effectively eliminating iron chlorosis by increasing uptake.

4. Agronomic Efficacy: Evidence from Case Studies

Recent field and greenhouse trials have demonstrated the versatility of HA across various crops.

4.1 Fruit Yield and Quality

- **Pear (*Pyrus communis* L.):** A study on 'Le Conte' pears compared foliar applications of Citric Acid (CA), Gibberellic Acid (GA3), and HA. Results indicated that higher concentrations of HA (5%) significantly improved vegetative growth parameters such as shoot length and leaf area compared to the control. Furthermore, HA 5% treatments resulted in superior fruit weight (g) and size compared to lower doses (Mosa et al., 2022).

- **Lemon (*Citrus limon*):** Research on 'Eureka' lemons evaluated water-soluble humic acid and fulvic acid potassium. These treatments significantly increased single fruit weight, edible rate, and juice yield while enhancing Vitamin C, total sugar, and soluble solid content (He et al., 2022).

- **Guava (*Psidium guajava* L.):** Foliar application of HA (60 ml/L) combined with bio-inoculants allowed for a reduction in inorganic NPK usage by 20% while improving fruit yield and weight (Ashwini et al., 2024).

4.2 Seed Germination and Seedling Vigor

In stone fruits, specifically Apricot (*Prunus armeniaca* L.), soaking seeds in a synergistic solution of GA3 (1500 mg/L) and HA (600 mg/L) proved most effective. This combination significantly increased germination percentages and improved seedling traits such as stem length, root length, and dry weight (Medan, 2023).

4.3 Abiotic Stress Mitigation

HA plays a protective role against environmental stress. A study on Egyptian Lime trees grown under saline conditions demonstrated that soil application of HA (20 ml/tree) mitigated salt stress. The treatment enhanced leaf nutrient content and significantly improved tree canopy volume and fruit quality metrics despite the saline soil (Ennab, 2016).

4.4 Method of Application: Foliar vs. Soil

In 'Paros' strawberries, the method of application influenced efficacy. Foliar applications of humic substances (specifically at 600–900 mg/L) were generally found to be more effective than soil drenching for increasing shoot dry mass, Vitamin C content, and overall yield (Eshghi and Garazhian, 2013).

5. Factors Influencing Efficiency

The efficacy of HA is not uniform and depends on several variables:

- **Source Material:** The origin of the HA (peat, coal, lignite, compost) dictates its chemical structure and nutrient composition.

- **Application Rate:** Effects are often dose-dependent. While high doses generally improve physical soil properties, excessive binding capacities can sometimes render micronutrients unavailable.

- **Soil and Environmental Conditions:** The response to HA varies by soil type (clay vs. sand) and stress conditions (salinity, drought).

6. Conclusion and Future Perspectives

Humic acid serves as a potent organic amendment that enhances soil fertility, promotes plant growth through hormonal pathways, and mitigates abiotic stress. The case studies reviewed confirm its positive impact on germination, yield, and fruit quality across diverse species. However, further research is needed to determine optimal HA application rates and timing for different crops and to conduct long-term field trials to assess the sustained impact of HA on soil-plant systems.

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