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EFFICIENCY OF NUTRIENT UPTAKE FROM FERTILIZERS
ENHANCED BY BIOSTIMULANTS

Alecsia-Timeea DUȚĂ¹, Karina CSONTI¹, Alina LAȚO¹, Adina BERBECEA¹, Radulov ISIDORA¹

University of Life Science "King Mihai I" from Timișoara

Abstract: Improving nutrient use efficiency (NUE) is a critical challenge in modern agriculture, as excessive fertilizer application leads to environmental degradation and increased production costs. Biostimulants have emerged as sustainable tools to enhance nutrient uptake and plant productivity. Recent studies highlight the synergistic effects of biostimulants—such as humic acids, microbial inoculants, and seaweed extracts—when applied in combination with conventional fertilizers. These compounds act through multiple mechanisms, including stimulation of root system development, activation of beneficial soil microorganisms, and regulation of plant hormonal and metabolic processes. Experimental evidence indicates significant improvements in the absorption and assimilation of macro- and micronutrients, leading to increased yield and nutritional quality of crops. However, variability in results across studies and the lack of standardized application protocols remain major limitations. Further research is needed to elucidate mechanisms of action, optimize formulations, and establish clear regulatory frameworks to ensure the effective and environmentally safe use of biostimulants in nutrient management strategies.

• Introduction

Biostimulants are defined as natural or synthetic substances and microorganisms that promote plant growth, nutrient uptake, and stress resilience independently of their nutrient content (Gunalarasi & Kumar, 2023; Pereira et al., 2025). These inputs encompass a wide array of categories, including humic substances, seaweed extracts, protein hydrolysates, microbial inoculants, and signaling molecules (Baltazar et al., 2021; García et al., 2020; Hafez et al., 2025). Their role in sustainable agriculture is increasingly recognized due to their capacity to enhance nutrient use efficiency (NUE) and improve crop performance under diverse environmental conditions. This review synthesizes current knowledge on the interactions between biostimulants and fertilizers, focusing on their role in enhancing NUE and promoting sustainable crop production. It addresses prevailing nutrient management challenges, categorizes major biostimulant types, elucidates their mechanisms of action, and evaluates factors influencing their effectiveness. Additionally, it highlights recent field-based evidence, integration strategies, and future directions for biostimulant innovation within the framework of climate-smart agriculture

• Material and method

A qualitative analysis was performed on publications released between 2020 and 2025, emphasizing studies that explore biostimulant contributions to nutrient use efficiency and fertilizer performance. Sources were gathered from reputable and accessible databases, including ScienceDirect, Elsevier, Scopus, Web of Science, and Google Scholar. Selection criteria prioritized peer-reviewed articles with open-access availability and direct relevance to biostimulant-fertilizer interactions. The reviewed literature was synthesized to extract key mechanisms, identify emerging trends, and assess practical implications for sustainable nutrient management in agricultural systems.

• Discussions

1. Fertilizer Use and Nutrient Uptake: Current Challenges

Nutrient uptake in plants involves complex physiological and biochemical pathways, including passive and active transport mechanisms. Nutrients enter root cells via diffusion, mass flow, and ion exchange, facilitated by membrane transporters and root exudates (Anitha, 2020; Khardia & Sharma, 2022). Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are absorbed as inorganic ions, while micronutrients like iron (Fe), zinc (Zn), and manganese (Mn) rely on chelation and redox reactions to remain bioavailable (Hafez et al., 2025; García et al., 2020). Uptake efficiency is shaped by root architecture, soil conditions, microbial activity, and organic compounds that influence nutrient solubility and metabolism (Basar et al., 2025; Pereira et al., 2025).

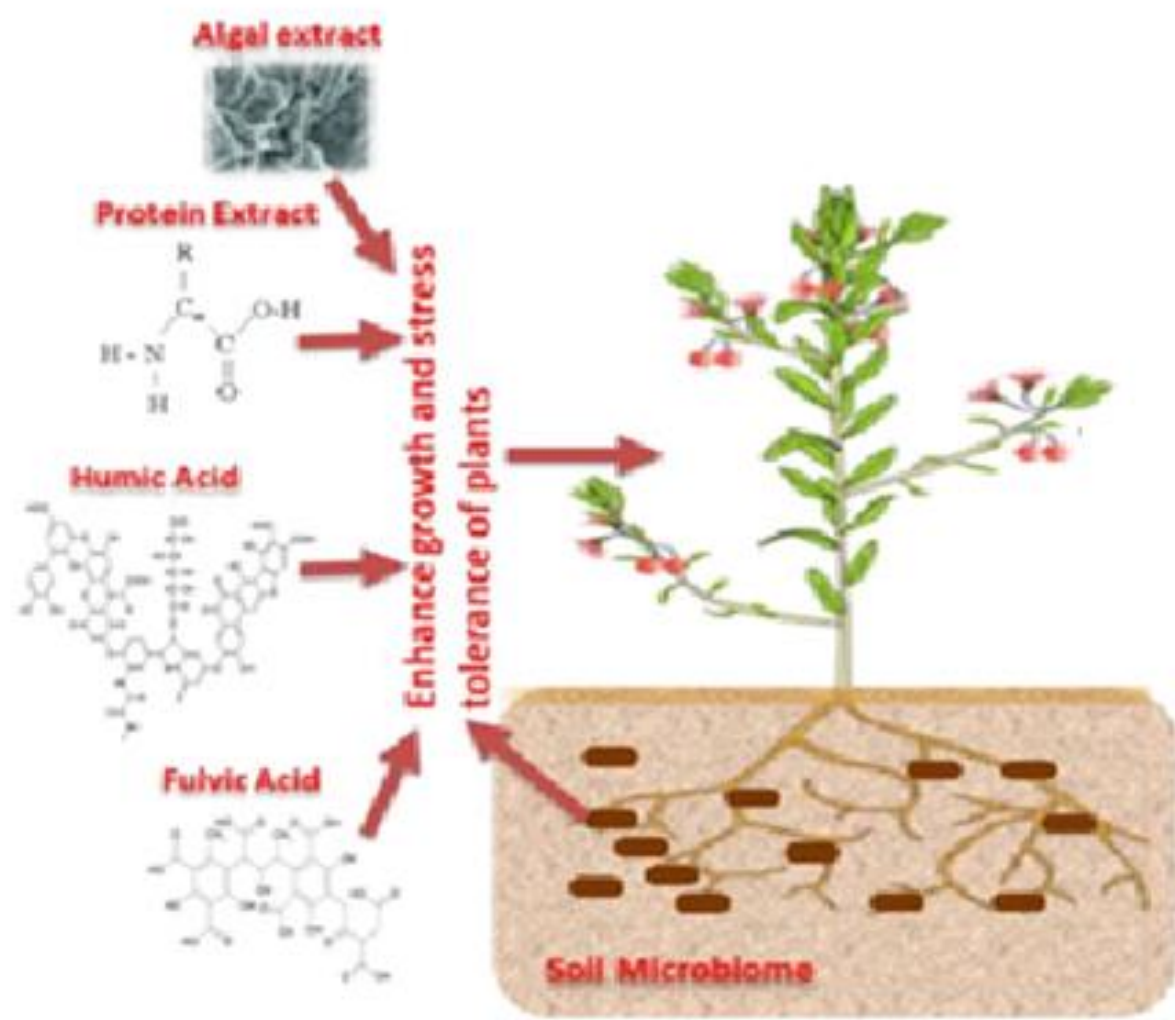


Figure 1. Role of biostimulants in plant development (Panday et al., 2022)

2. Biostimulants: Classification and Mechanisms

Classification and Mechanisms of Biostimulants			
Biostimulant Type	Key Components	Primary Functions	Mechanisms of Action
Humic Substances	Humic and fulvic acids	Improve soil structure, root growth, and micronutrient mobility	Chelation, cation exchange, stimulation of root elongation [García et al., 2020; Hafez et al., 2025]
Seaweed Extracts	Polysaccharides, phytohormones, antioxidants	Enhance chlorophyll synthesis, stress tolerance, and root proliferation	Hormonal modulation, antioxidant activation [Mounaimi et al., 2024; Fasani et al., 202]
Protein Hydrolysates	Amino acids, peptides	Boost nitrogen assimilation, photosynthesis, and crop quality	Signaling molecule activity, nutrient transport enhancement [Gunalarasi & Kumar, 2023; Pereira et al., 2025]
Microbial Inoculants	PGPR, mycorrhizal fungi	Improve nutrient solubilization, water uptake, and symbiotic interactions	Nitrogen fixation, phosphorus solubilization, rhizosphere enhancement [Ruzzi et al., 2024; Mounaimi et al., 2024]
Other Compounds	Chitosan, silicon, phenolic extracts	Strengthening plant defenses and stress resilience	Elicitation of defense responses, cell wall reinforcement [Baltazar et al., 2021; Boutahiri et al., 2024]

Factors Influencing Biostimulant Efficiency

Factor	Influence on Biostimulant Performance	References
Crop Species & Genotype	Different species and cultivars vary in responsiveness due to genetic and physiological traits.	Pereira et al., 2025; Fasani et al., 2025
Growth Stage	Early application enhances root and leaf growth; later stages support nutrient translocation and stress tolerance.	Gunalarasi & Kumar, 2023; Ruzzi et al., 2024
Soil Properties	Texture, pH, organic matter, and fertility affect nutrient availability and microbial activity.	García et al., 2020; Hafez et al., 2025
Soil Fertility Level	Greater benefits in nutrient-poor soils; limited response in already fertile conditions.	Basar et al., 2025; Maaz et al., 2025
Climate Conditions	Temperature, rainfall, and radiation influence biostimulant stability and plant stress response.	Baltazar et al., 2021; Boutahiri et al., 2024
Application Method	Foliar sprays offer rapid uptake; soil or seed treatments provide sustained effects.	Gunalarasi & Kumar, 2023; Fasani et al., 2025
Formulation & Stability	Liquid vs. granular forms, concentration, and compatibility with other inputs affect efficacy.	Ruzzi et al., 2024; Hafez et al., 2025
Synergistic Combinations	Combining biostimulants (e.g., humic acids + microbes) can enhance nutrient uptake and stress resilience.	Pereira et al., 2025; Mounaimi et al., 2024

• Conclusions

Enhancing nutrient use efficiency (NUE) is a critical priority for modern agriculture, given the mounting challenges of soil degradation, climate variability, and the environmental costs of fertilizer overuse. This review highlights the growing potential of biostimulants as complementary tools that improve nutrient uptake, optimize fertilizer performance, and support sustainable crop production. By acting through diverse physiological and biochemical mechanisms, biostimulants—ranging from humic substances and microbial inoculants to seaweed extracts and protein hydrolysates—can significantly enhance root development, nutrient solubilization, and stress resilience. The integration of biostimulants into conventional and precision-based fertilization strategies offers a promising pathway toward more efficient and climate-smart nutrient management. Field evidence confirms their synergistic benefits in improving yield, nutrient recovery, and soil health while reducing environmental losses and input dependency. As scientific innovation continues to refine biostimulant formulations and delivery systems, their role in regenerative and low-input farming systems is expected to expand. Ultimately, biostimulants represent a transformative approach to nutrient management—one that aligns agronomic performance with ecological stewardship and long-term sustainability. Their strategic deployment will be essential in building resilient agroecosystems capable of meeting future food security and environmental goals