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Biostimulants and Biofertilizers in Sustainable Agriculture

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ABSTRACT

The escalating global demand for food coupled with the environmental degradation caused by excessive use of synthetic agrochemicals necessitates a paradigm shift toward sustainable agricultural practices. Biostimulants and biofertilizers have emerged as promising eco-friendly alternatives that enhance crop productivity while preserving soil health and ecosystem integrity. Biostimulants, including humic substances, seaweed extracts, amino acids, protein hydrolysates, and chitosan, function through modulation of plant physiological and molecular processes to improve nutrient use efficiency, stress tolerance, and crop quality. Biofertilizers, comprising beneficial microorganisms such as nitrogen-fixing bacteria (Rhizobium, Azotobacter), phosphate-solubilizing bacteria, and arbuscular mycorrhizal fungi (AMF), enhance nutrient availability through biological processes. This review comprehensively examines the classification, mechanisms of action, synergistic effects, regulatory frameworks, and market trends of biostimulants and biofertilizers. The integration of these biological inputs offers a viable strategy for achieving sustainable food production, reducing environmental pollution, and ensuring long-term agricultural resilience in the context of climate change.

Keywords: *Biostimulants; Biofertilizers; Sustainable Agriculture; Plant Growth-Promoting Rhizobacteria; Nutrient Use Efficiency.*

INTRODUCTION

The global population is projected to reach approximately 10 billion by 2050, necessitating a substantial increase in agricultural production to meet the rising food demand (Calvo et al., 2014). Conventional agricultural practices heavily rely on synthetic chemical fertilizers and pesticides, which have contributed significantly to soil degradation, water contamination, biodiversity loss, and greenhouse gas emissions (Bhardwaj et al., 2014). The indiscriminate application of chemical fertilizers has led to nutrient imbalances in soil, reduced soil organic matter content, and deterioration of soil microbial communities.

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Furthermore, it is estimated that approximately 40–70% of nitrogen, 80–90% of phosphorus, and 50–70% of potassium from applied synthetic fertilizers are lost to the environment and cannot be absorbed by plants (Sharif et al., 2018).

In response to these challenges, there has been a growing global interest in sustainable agricultural approaches that minimize environmental impact while maintaining or improving crop productivity. Biostimulants and biofertilizers represent two distinct but complementary categories of biological inputs that have gained significant attention in modern agriculture (du Jardin, 2015). The European Union Regulation 2019/1009 has formally recognized biostimulants as fertilizing products, defining plant biostimulants as products that stimulate plant nutrition processes independently of the product's nutrient content, aiming to improve nutrient use efficiency, tolerance to abiotic stress, quality traits, and availability of confined nutrients in the soil or rhizosphere (European Parliament, 2019).

Biostimulants encompass a diverse range of substances including humic and fulvic acids, seaweed extracts, amino acids and protein hydrolysates, chitosan and other biopolymers, and beneficial microorganisms (Yakhin et al., 2017). Biofertilizers, on the other hand, are preparations containing living microorganisms that colonize the rhizosphere or interior of plants and promote growth by increasing the supply or availability of primary nutrients (Vessey, 2003). The global biostimulants market was valued at approximately USD 4.1 billion in 2024 and is projected to reach USD 7.84 billion by 2030, growing at a compound annual growth rate (CAGR) of 11.9% (Markets and Markets, 2025). This remarkable growth underscores the increasing adoption and acceptance of these biological inputs in mainstream agriculture.

This review aims to provide a comprehensive analysis of biostimulants and biofertilizers, encompassing their classification, mechanisms of action, effects on crop productivity, role in stress management, regulatory landscape, and future perspectives in the context of sustainable agriculture.

2. Classification of Biostimulants and Biofertilizers

2.1 Types of Biostimulants

Plant biostimulants are broadly classified into non-microbial and microbial categories. According to du Jardin (2015), the major categories include: (a) humic and fulvic acids, (b) seaweed and plant extracts, (c) protein hydrolysates and amino acids, (d) chitosan and other biopolymers, and (e) beneficial fungi and bacteria.

Humic substances, particularly humic acid (HA) and fulvic acid (FA), are derived from the decomposition of organic matter and represent one of the most widely used biostimulant categories. They account for a significant market share, with the acid-based biostimulant segment valued at USD 1.82 billion in 2024 (Global Market Insights, 2025). Humic acids improve soil structure, enhance cation exchange capacity (CEC), and stimulate root growth through auxin-like activity (Canellas et al., 2015). Fulvic acids, being smaller molecules, can penetrate plant cell membranes more efficiently, facilitating nutrient transport and enhancing seed germination (Nardi et al., 2021).

Seaweed extracts, predominantly derived from brown algae such as *Ascophyllum nodosum*, contain bioactive compounds including polysaccharides, polyphenols, phytohormones (cytokinins, auxins), and osmoprotectants. These extracts have demonstrated the ability to enhance plant growth, improve nutrient uptake, and increase tolerance to abiotic stresses such as drought and salinity (Ali et al., 2021). Protein hydrolysates (PHs) are mixtures of peptides and amino acids obtained through chemical or enzymatic hydrolysis of animal or plant-derived proteins. They stimulate carbon and nitrogen metabolism, improve nutrient assimilation, and modulate root architecture (Colla et al., 2017). Chitosan, a biopolymer derived from chitin in crustacean shells, functions as both a biostimulant and an elicitor of plant defense mechanisms, stimulating pathogenesis-related protein expression and phytoalexin production (Sharif et al., 2018).

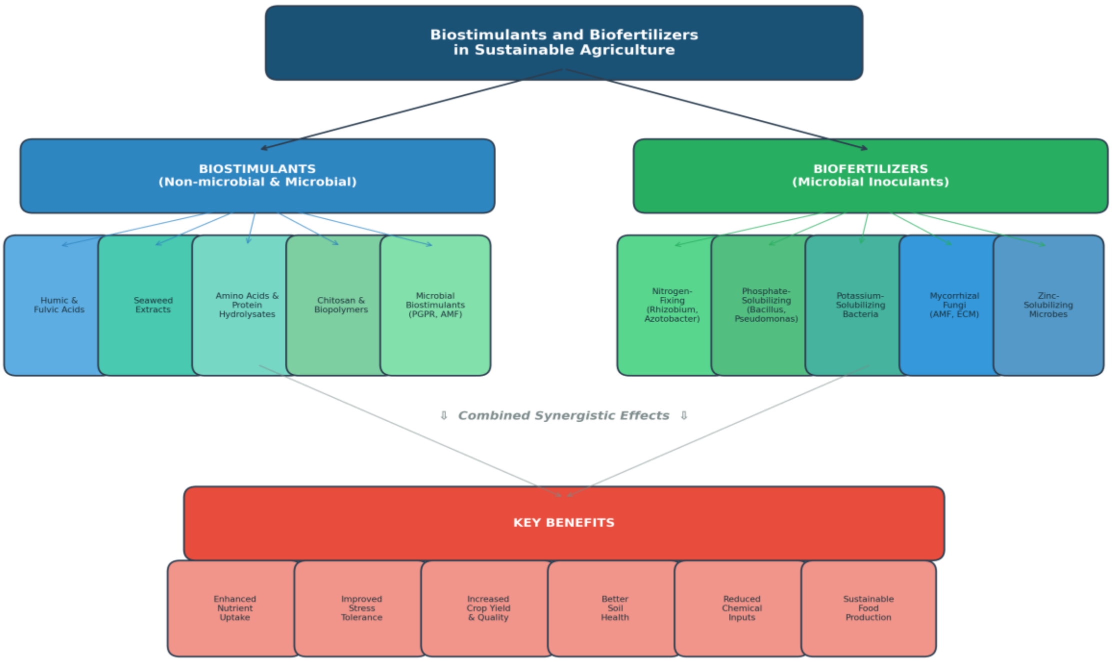

Figure 1: Classification of Biostimulants and Biofertilizers in Sustainable Agriculture

2.2 Types of Biofertilizers

Biofertilizers are classified based on the type of microorganisms they contain and their primary function in nutrient cycling. The major categories include:

Nitrogen-fixing biofertilizers: These contain bacteria capable of converting atmospheric nitrogen (N^2) into plant-available ammonium (NH^4). Symbiotic nitrogen fixers such as *Rhizobium* species form nodules on leguminous plant roots, while free-living fixers like *Azotobacter* and *Azospirillum* associate with the rhizosphere of diverse crops (Vessey, 2003). According to Herridge et al. (2008), rhizobial inoculants can reduce annual nitrogen fertilization costs by approximately USD 29 per hectare.

Phosphate-solubilizing biofertilizers: Species of *Bacillus*, *Pseudomonas*, and *Aspergillus* solubilize insoluble phosphate compounds through the production of organic acids, phosphatases, and siderophores, making phosphorus available for plant uptake (Gouda et al., 2018).

Mycorrhizal biofertilizers: Arbuscular mycorrhizal fungi (AMF) form symbiotic associations with approximately 80% of terrestrial plant species, extending the root absorption zone through their extensive hyphal network. A meta-analysis by Zhang et al. (2022) demonstrated that AMF inoculation increased crop yields by an average of 23% under rainfed conditions, with improvements attributed to enhanced nutrient uptake, photosynthesis, and stress resistance.

3. Mechanisms of Action

Biostimulants and biofertilizers influence plant growth through multiple interconnected mechanisms that operate at molecular, cellular, and whole-plant levels (Rouphael & Colla, 2020). Understanding these mechanisms is critical for optimizing their application and developing more effective formulations.

3.1 Nutrient Mobilization and Uptake Enhancement

One of the primary mechanisms through which biofertilizers function is biological nitrogen fixation. The nitrogenase enzyme complex in diazotrophic bacteria catalyzes the conversion of atmospheric N^2 to NH^3, providing a sustainable nitrogen source for crops (Bhardwaj et al., 2014). Phosphate-solubilizing microorganisms release organic acids such as gluconic, citric, and oxalic acids that lower rhizosphere pH, dissolving insoluble phosphate minerals and increasing plant-available phosphorus by 20–30% (Gouda et al., 2018). Humic substances enhance nutrient uptake by stimulating H^+-ATPase activity in root cell plasma membranes, generating proton electrochemical gradients that energize secondary ion transporters for nitrate, potassium, and micronutrient absorption (Canellas et al., 2015). Seaweed extracts have been shown to upregulate genes encoding root nutrient transporters, including BnNRT1.1 and BnNRT2.1 for nitrogen uptake and BnSultr4.1 for sulfur acquisition (Ali et al., 2021).

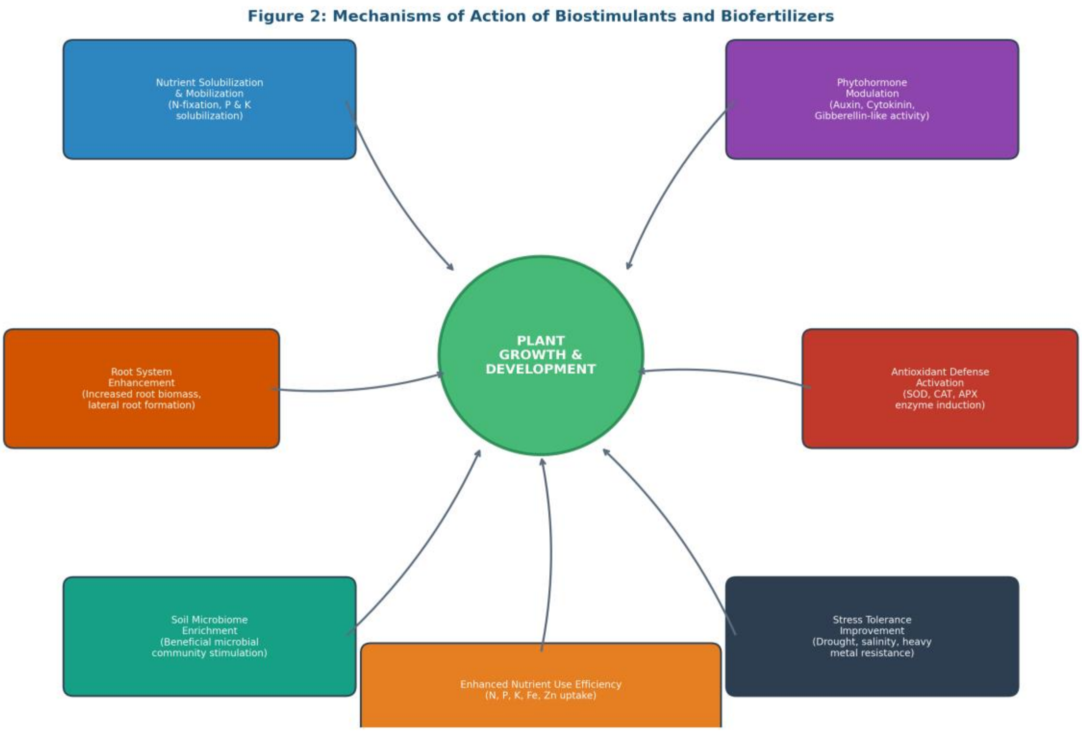

Figure 2: Mechanisms of Action of Biostimulants and Biofertilizers on Plant Growth

3.2 Phytohormone Modulation

Both biostimulants and biofertilizers modulate endogenous plant hormone levels, either through direct supply of hormone-like compounds or by stimulating endogenous biosynthesis pathways. Seaweed extracts contain cytokinins and auxin precursors that promote cell division and elongation (Battacharyya et al., 2015). Humic acids exhibit auxin-like activity, stimulating lateral root initiation and root hair development (Canellas et al., 2015). Many PGPR strains produce indole-3-acetic acid (IAA), gibberellins, and cytokinins that directly influence plant growth patterns and developmental processes (Gouda et al., 2018). Protein hydrolysates contain signaling peptides that interact with auxin and gibberellin response pathways, as demonstrated through studies with gibberellic acid-deficient mutants (Colla et al., 2017).

3.3 Stress Tolerance and Antioxidant Defense

Biostimulants play a pivotal role in enhancing plant tolerance to abiotic stresses including drought, salinity, heavy metals, and extreme temperatures. They promote the accumulation of compatible solutes (proline, glycine betaine) and activate antioxidant defense systems comprising superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and peroxidase (POD) enzymes (Rouphael & Colla, 2020). Chitosan acts as an elicitor of plant immune responses, triggering the salicylic acid and jasmonic acid signaling pathways, inducing expression of pathogenesis-related (PR) proteins, and stimulating phytoalexin biosynthesis (Sharif et al., 2018). AMF colonization improves water relations under drought stress by enhancing aquaporin gene expression and hydraulic conductivity in root cells (Zhang et al., 2022).

4. Role in Enhancing Crop Productivity

Extensive field and greenhouse studies have demonstrated the significant positive effects of biostimulants and biofertilizers on crop yield and quality parameters. Biofertilizers, when used in combination with chemical fertilizers, can increase crop yields by 10–40% while replacing approximately 25–30% of chemical fertilizer inputs (Malusá & Vassilev, 2014). The meta-analysis conducted by Zhang et al. (2022) on arbuscular mycorrhizal fungi revealed that AMF inoculation increased crop yields by 23% on average, with shoot biomass increasing by 24.2% and root biomass by 29.6% under rainfed conditions.

Seaweed-based biostimulants have shown remarkable efficacy across diverse crop species. In tomato (*Solanum lycopersicum*), *Ascophyllum nodosum* extracts increased germination rate, seedling vigor, chlorophyll content, fruit yield, and quality while improving resistance to pathogens including *Verticillium dahliae* and *Alternaria solani* (Ali et al., 2021). Humic acid application, when combined with chemical fertilizers in fertigation, demonstrated the ability to replace up to 20% of synthetic fertilizer requirements while improving nitrogen, phosphorus, and potassium use efficiencies by 16.4%, 9.3%, and 18.3%, respectively (Nardi et al., 2021).

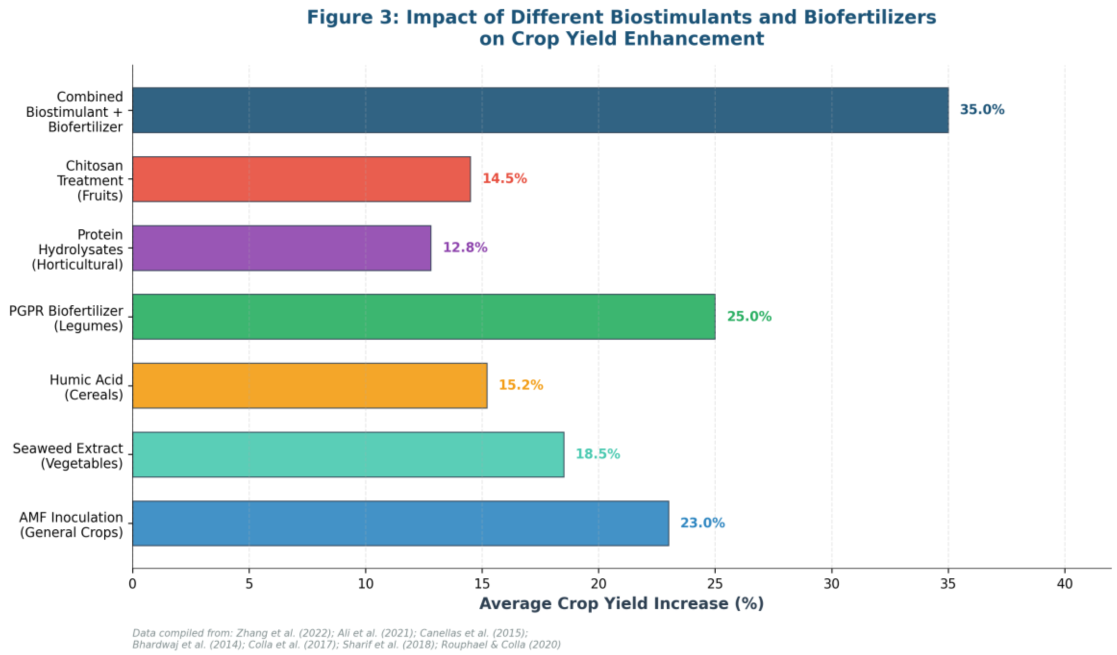

Figure 3: Impact of Different Biostimulants and Biofertilizers on Crop Yield Enhancement

4.1 Comparative Effects of Major Biostimulants

Table 1: Comparative effects of major biostimulants and biofertilizers on crop productivity

Biostimulant Type	Primary Mechanism	Crop Response	Reference
Humic & Fulvic Acids	H+-ATPase activation, auxin-like root stimulation	12–20% yield increase, improved NUE	Canellas et al. (2015)
Seaweed Extracts	Phytohormone supply, gene regulation	15–25% yield increase, stress tolerance	Ali et al. (2021)
Protein Hydrolysates	N/C metabolism stimulation, root modulation	10–18% yield increase, quality improvement	Colla et al. (2017)
AMF Inoculation	Extended root network, P acquisition	23% average yield increase	Zhang et al. (2022)
Rhizobium Inoculants	Biological N fixation in legumes	25–35% yield increase in legumes	Vessey (2003)
Chitosan	Defense elicitation, controlled nutrient release	10–15% yield increase, disease suppression	Sharif et al. (2018)

5. Synergistic Effects and Integrated Application Strategies

The combined application of biostimulants and biofertilizers has demonstrated synergistic effects that exceed the benefits of individual application. Rouphael and Colla (2020) emphasized that the synergy between microbial and non-microbial biostimulants is paving the way for the development of biopreparations that can significantly improve yield performance. The integration of seaweed extracts with AMF inoculants has been shown to enhance root colonization rates, improve nutrient uptake, and increase plant biomass production beyond what either input achieves alone (Battacharyya et al., 2015).

The concept of integrated biostimulant management involves the strategic combination of different categories of biostimulants with biofertilizers, tailored to specific crop requirements, soil conditions, and environmental stressors. For instance, the combination of humic acids with phosphate-solubilizing bacteria creates a dual mechanism where humic substances enhance root development and nutrient transport capacity while the bacteria increase phosphorus availability in the rhizosphere (Nardi et al., 2021). Similarly, co-application of protein hydrolysates with PGPR has been reported to improve nitrogen assimilation and stimulate secondary metabolism in crops under stress conditions (Colla et al., 2017). Studies show that integrated approaches can increase crop yields by up to 35%, significantly exceeding the individual contributions of each component (Malusá & Vassilev, 2014).

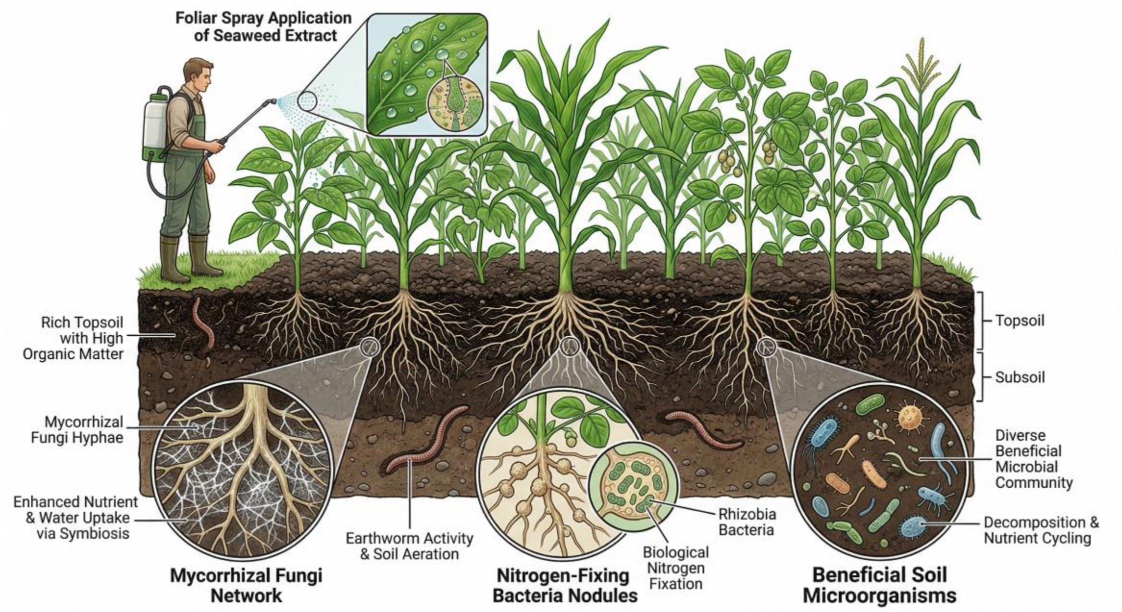

Figure 5: Integrated Biostimulant and Biofertilizer Application in Sustainable Agriculture

6. Regulatory Framework and Market Trends

The regulatory landscape for biostimulants has evolved significantly in recent years. The European Union’s Fertilizing Products Regulation (EU) 2019/1009, which came into force in July 2022, represents a landmark achievement by establishing a harmonized framework for the marketing of fertilizing products, including biostimulants, across all EU member states (European Parliament, 2019). This regulation formally defines plant biostimulants as a distinct product category and establishes quality, safety, and labeling requirements for their commercialization.

The global biostimulants market has witnessed remarkable growth, driven by increasing demand for sustainable agricultural solutions, favorable government policies, and growing consumer awareness of food safety and environmental concerns. The market was valued at USD 4.1 billion in 2024, with projections reaching USD 4.6 billion in 2025 and USD 7.84 billion by 2030, growing at a CAGR of 11.9% (Market sand Markets, 2025). Europe dominates the market with a 40.5% share, attributed to stringent regulations on chemical inputs and strong institutional support for sustainable farming. The foliar treatment segment holds the largest market share at 71.2%, while the microbial amendment segment is expected to register the highest growth rate of 13.0% (Global Market Insights, 2025). Key industry players including BASF SE, Bayer, Lallemand, Syngenta, and Yara International collectively held approximately 47% of the market share in 2024.

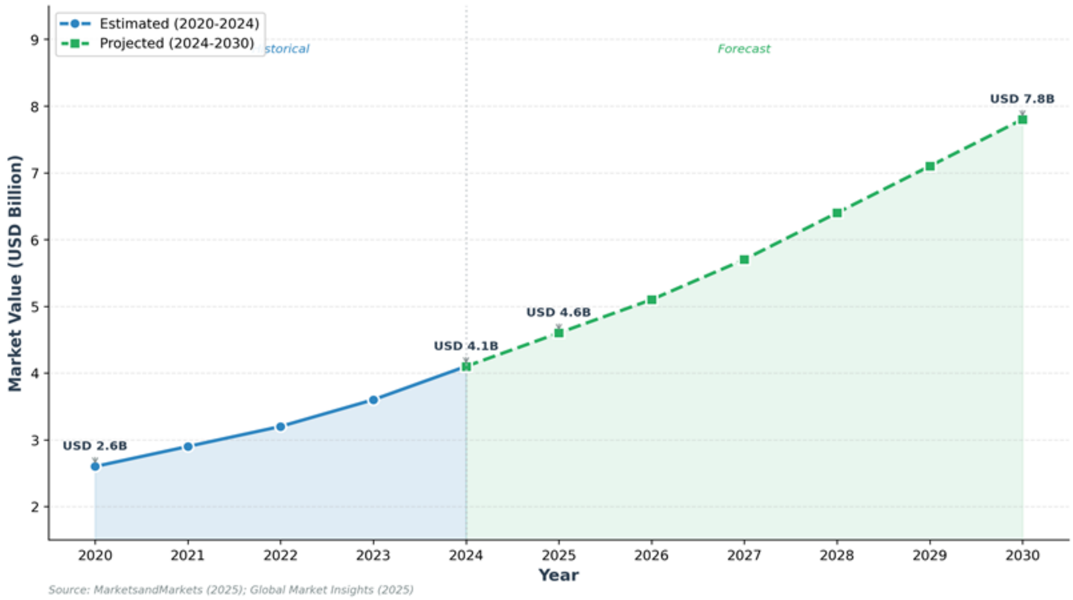

Figure 4: Global Biostimulants Market Size and Growth Projection (2020–2030)

7. Challenges and Future Perspectives

Despite the promising potential of biostimulants and biofertilizers, several challenges remain in their widespread adoption. Variability in product efficacy due to differences in raw material sources, manufacturing processes, and environmental conditions represents a major limitation (Yakhin et al., 2017). The lack of standardized methodologies for evaluating biostimulant effects across different agroclimatic zones hinders the development of universally applicable products. Furthermore, the complex multi-component nature of many biostimulants makes it difficult to establish clear cause-effect relationships and regulatory classification.

Future research should focus on: (a) elucidating the molecular and genetic mechanisms underlying biostimulant action through advanced omics technologies (genomics, transcriptomics, proteomics, and metabolomics); (b) developing standardized bioassays and quality control protocols; (c) exploring nanotechnology-based delivery systems for enhanced biostimulant efficacy; (d) investigating the role of artificial intelligence and precision agriculture in optimizing biostimulant application; and (e) assessing the long-term effects of biostimulant use on soil microbiome dynamics and ecosystem services (Rouphael & Colla, 2020). The integration of biostimulants with emerging technologies such as Internet of Things (IoT) sensors and drone-based application systems holds significant promise for achieving targeted, site-specific biostimulant delivery in modern farming systems.

CONCLUSION

Biostimulants and biofertilizers represent indispensable tools in the transition toward sustainable agriculture, offering environmentally compatible solutions for enhancing crop productivity, nutrient use efficiency, and stress resilience. This review has demonstrated that these biological inputs operate through diverse and interconnected mechanisms including nutrient mobilization, phytohormone modulation, antioxidant defense activation, and beneficial soil microbiome enrichment. The evidence from extensive field trials confirms yield increases of 10–35% across various crop species, with the combined application of biostimulants and biofertilizers showing synergistic effects that exceed individual treatments.

The growing biostimulants market, projected to reach USD 7.84 billion by 2030, along with the establishment of regulatory frameworks such as EU Regulation 2019/1009, signals the mainstream acceptance of these products in global agriculture. However, the full realization of the biostimulant potential requires continued investment in research to elucidate mechanisms of action, develop standardized evaluation protocols, and optimize formulations for different agroclimatic conditions. The integration of biostimulants and biofertilizers into comprehensive crop management strategies, supported by precision agriculture technologies, will be essential for achieving sustainable food security in the face of climate change and population growth. The scientific community, industry stakeholders, and policymakers must collaborate to facilitate the development, regulation, and dissemination of these promising biological inputs for the benefit of global agriculture and environmental sustainability.

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All authors have participated in critically revising of the entire manuscript and approval of the final manuscript.

REFERENCES

Ali, O., Ramsubhag, A., & Jayaraman, J. (2021). Biostimulant properties of seaweed extracts in plants: Implications towards sustainable crop production. *Plants, 10*(3), 531. https://doi.org/10.3390/plants10030531

Battacharyya, D., Babgohari, M. Z., Rathor, P., & Prithiviraj, B. (2015). Seaweed extracts as biostimulants in horticulture. *Scientia Horticulturae, 196*, 39–48. https://doi.org/10.1016/j.scienta.2015.09.012

Bhardwaj, D., Ansari, M. W., Sahoo, R. K., & Tuteja, N. (2014). Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. *Microbial Cell Factories, 13*, 66. https://doi.org/10.1186/1475-2859-13-66

Calvo, P., Nelson, L., & Kloepper, J. W. (2014). Agricultural uses of plant biostimulants. *Plant and Soil, 383*(1–2), 3–41. https://doi.org/10.1007/s11104-014-2131-8

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. *Scientia Horticulturae, 196*, 15–27. https://doi.org/10.1016/j.scienta.2015.09.013

Colla, G., Hoagland, L., Ruzzi, M., Cardarelli, M., Bonini, P., Canaguier, R., & Rouphael, Y. (2017). Biostimulant action of protein hydrolysates: Unraveling their effects on plant physiology and microbiome. *Frontiers in Plant Science, 8,* 2202. https://doi.org/10.3389/fpls.2017.02202

du Jardin, P. (2015). Plant biostimulants: Definition, concept, main categories and regulation. *Scientia Horticulturae,* *196*, 3–14. https://doi.org/10.1016/j.scienta.2015.09.021

Parliament, E. (2019). Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products. *Official Journal of the European Union, L 170*, 1–114.

Gouda, S., Kerry, R. G., Das, G., Paramithiotis, S., Shin, H. S., & Patra, J. K. (2018). Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. *Microbiological Research, 206*, 131–140. https://doi.org/10.1016/j.micres.2017.08.016

Herridge, D. F., Peoples, M. B., & Boddey, R. M. (2008). Global inputs of biological nitrogen fixation in agricultural systems. *Plant and Soil*, *311*(1–2), 1–18. https://doi.org/10.1007/s11104-008-9668-3

Malusá, E., & Vassilev, N. (2014). A contribution to set a legal framework for biofertilisers. *Applied Microbiology and Biotechnology, 98*(15), 6599–6607. https://doi.org/10.1007/s00253-014-5828-y

Nardi, S., Pizzeghello, D., Muscolo, A., & Vianello, A. (2021). Physiological effects of humic substances on higher plants. *Soil Biology and Biochemistry, 34*(11), 1527–1536. https://doi.org/10.1016/S0038-0717(02)00174-8

Rouphael, Y., & Colla, G. (2020). Editorial: Biostimulants in agriculture. *Frontiers in Plant Science, 11*, 40. https://doi.org/10.3389/fpls.2020.00040

Sharif, R., Mujtaba, M., Ur Rahman, M., Shalmani, A., Ahmad, H., Anwar, T., Tianchan, D., & Wang, X. (2018). The multifunctional role of chitosan in horticultural crops; A review. *Molecules, 23*(4), 872. https://doi.org/10.3390/molecules23040872

Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil, 255*(2), 571–586. https://doi.org/10.1023/A:1026037216893

Yakhin, O. I., Lubyanov, A. A., Yakhin, I. A., & Brown, P. H. (2017). Biostimulants in plant science: A global perspective. *Frontiers in Plant Science*, *7*, 2049. https://doi.org/10.3389/fpls.2016.02049

Zhang, F., Wang, P., Zou, Y. N., Wu, Q. S., & Kuča, K. (2022). Arbuscular mycorrhizal fungi increase crop yields by improving biomass under rainfed condition: A meta-analysis. *Peer J, 10*, e12861. https://doi.org/10.7717/peerj.12861