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Biofertilizers and Biostimulants for Sustainable Crop Production: Current Status and Emerging Trends

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ABSTRACT

Biofertilizers and biostimulants have emerged as sustainable alternatives to conventional agrochemicals, enhancing crop productivity while minimizing environmental impacts. Biofertilizers improve nutrient availability through biological nitrogen fixation, phosphate solubilization, and beneficial microbial interactions, whereas biostimulants enhance plant growth, nutrient uptake, stress tolerance, and soil health through natural compounds and microbial metabolites. Recent advances in microbial consortia, seaweed extracts, humic substances, protein hydrolysates, and nanotechnology-based formulations have expanded their agricultural applications. Emerging trends emphasize precision agriculture, climate-resilient farming, and integrated nutrient management. Their widespread adoption can improve soil fertility, reduce chemical fertilizer dependence, and promote sustainable, resilient, and environmentally friendly crop production systems.

Keywords: *Biofertilizers; biostimulants; PGPR; sustainable agriculture; nutrient use efficiency.*

INTRODUCTION

Global food security and environmental sustainability are increasingly viewed as inseparable challenges. The Green Revolution lifted yields of staple cereals through high-yielding varieties, irrigation and mineral fertilizers, but its long-term reliance on synthetic nitrogen, phosphorus and potassium fertilizers has reduced soil organic carbon, accelerated micronutrient depletion and contributed to eutrophication of surface waters (Tilman et al., 2002; & FAO, 2017). At the same time, the world must produce roughly 60% more food by 2050 to feed an expected population of 9.7 billion (FAO, 2017). Reconciling productivity with ecological integrity therefore demands inputs that maintain or increase yields while restoring soil biology and reducing greenhouse-gas emissions.

Biofertilizers and biostimulants are two such classes of inputs that have moved from niche research to mainstream policy in the past decade.

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Biofertilizers are formulations of living microorganisms that, when applied to seeds, plant surfaces or the rhizosphere, colonize the plant interior or its surroundings and promote growth by enhancing the supply or availability of primary nutrients (Vessey, 2003). Biostimulants are a more recent category, defined by the European Union Regulation 2019/1009 (which became fully applicable on 16 July 2022) as products that stimulate plant nutrition processes independently of nutrient content, with the aim of improving nutrient use efficiency, abiotic stress tolerance, crop quality traits or rhizosphere nutrient availability (European Parliament and Council, 2019).

2. Biofertilizers: Concept, Classification and Mechanisms

2.1 Concept and historical development

The concept of biofertilization originated with Hellriegel and Wilfarth in the late nineteenth century, who demonstrated that leguminous plants fix atmospheric nitrogen in symbiosis with root-nodule bacteria (Hellriegel & Wilfarth, 1888, as cited in Bhardwaj et al., 2014). Commercial production of Rhizobium inoculants began with the registration of "Nitragin" in the United States in 1896, and similar products were soon introduced in Europe and India. Vessey (2003) provided one of the most influential modern definitions, describing a biofertilizer as a substance that contains living microorganisms which, when applied to seed, plant surfaces or soil, colonizes the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant.

2.2 Functional classification

Biofertilizers are conventionally grouped into four functional categories: (i) nitrogen-fixing inoculants, (ii) phosphate-solubilizing and -mobilizing inoculants, (iii) potassium-solubilizing inoculants, and (iv) mycorrhizal fungi and other plant-growth-promoting microorganisms (Mahanty et al., 2017). Nitrogen-fixing biofertilizers include symbiotic genera such as Rhizobium, Bradyrhizobium and Frankia, associative diazotrophs such as Azospirillum and free-living forms such as Azotobacter and Cyanobacteria. Phosphate-solubilizing microorganisms (PSM), including Bacillus megaterium, Pseudomonas striata and fungi of the genera Aspergillus and Penicillium, secrete organic acids that solubilize inorganic phosphates such as tricalcium and rock phosphate (Khan et al., 2009). Potassium-solubilizing organisms such as Frateuria aurantia and Bacillus mucilaginosus release potassium from mica, feldspar and other silicate minerals (Meena et al., 2014). Arbuscular mycorrhizal (AM) fungi extend the effective absorptive surface of roots and improve uptake of phosphorus, zinc and water, particularly in low-input systems (Smith & Read, 2008). Figure 1 summarizes this classification.

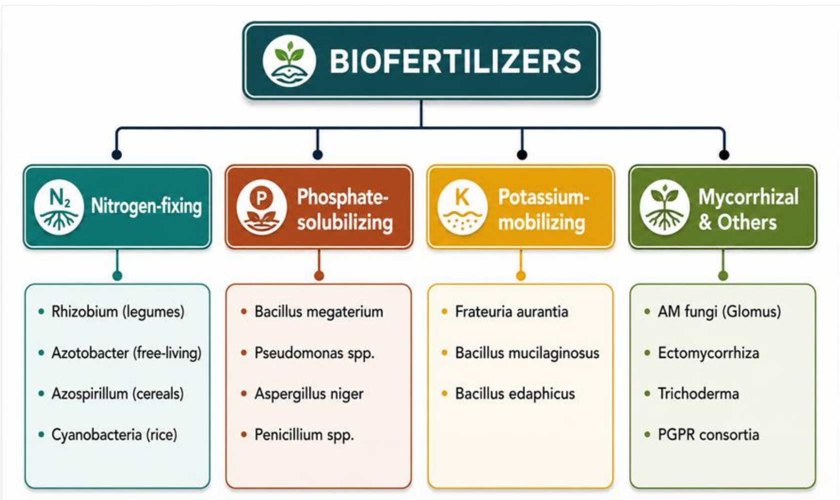

Figure1. Classification of biofertilizers based on functional groups.

2.3 Mechanisms of plant growth promotion

Glick (2012) classified the mechanisms by which biofertilizers and plant-growth-promoting rhizobacteria (PGPR) promote growth into direct and indirect categories. Direct mechanisms include biological nitrogen fixation, solubilization and mineralization of phosphorus, potassium and zinc, production of phytohormones such as indole-3-acetic acid (IAA), cytokinins and gibberellins, and the secretion of siderophores that chelate iron and make it available to plants. Indirect mechanisms include the production of antibiotics, lytic enzymes such as chitinases and beta-1,3-glucanases, induced systemic resistance (ISR) against pathogens, and the synthesis of 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which lowers plant ethylene levels and mitigates abiotic stress (Vejan et al., 2016; & Backer et al., 2018). Figure 2 illustrates these dual pathways.

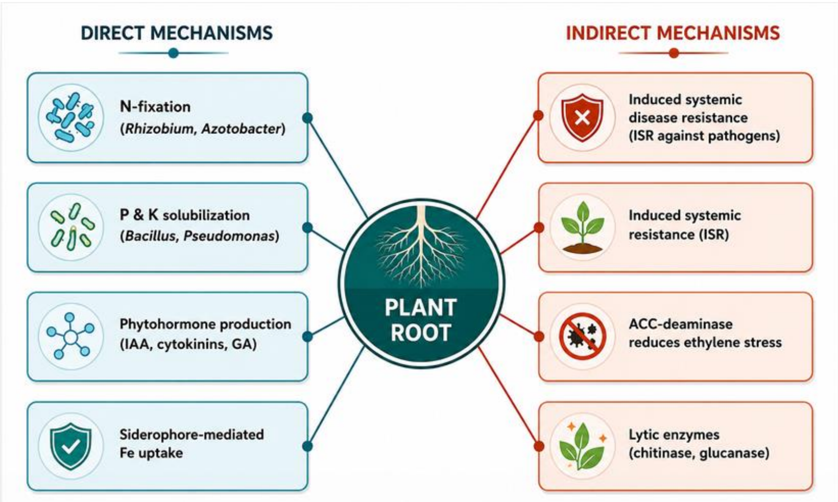

Figure2. Direct and indirect mechanisms by which biofertilizers promote plant growth.

2.4 Agronomic performance

Meta-analyses and multi-location trials have consistently demonstrated yield and nutrient-uptake benefits from biofertilizers. Schütz et al. (2018) reviewed 171 publications and reported a mean grain-yield increase of 8.5% for inoculation with PGPR across cereal crops, with the strongest effects under nutrient-limited and water-stressed conditions. Rhizobium inoculation of soybean, chickpea and groundnut has been shown to fix 50–200 kg N ha-1 per season, frequently replacing 25–50% of the recommended nitrogen dose (Mahanty et al., 2017). Co-inoculation of Azospirillum brasilense with maize has been associated with yield gains of 7–15% under reduced nitrogen fertilization (Hungria et al., 2010). AM fungi typically increase plant phosphorus uptake by 50–200% under low-P soils, particularly benefiting horticultural crops such as tomato and onion (Smith & Read, 2008).

3. Biostimulants: Definition, Categories and Modes of Action

3.1 Evolving definitions

Biostimulants are functionally distinct from biofertilizers because they are defined by the physiological response they elicit rather than by their composition. Du Jardin (2015) proposed an influential definition: "a plant biostimulant is any substance or microorganism applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, regardless of its nutrient content." This definition was substantially adopted by the European Union under Regulation 2019/1009, which created a new Product Function Category (PFC 6) for plant biostimulants with four permissible claims: improved nutrient use efficiency, abiotic stress tolerance, quality traits, and availability of confined nutrients (European Parliament and Council, 2019). The United States Farm Bill (2018) and India's Fertilizer

(Control) Order amendment (2021) introduced comparable functional definitions, signalling international convergence on the concept.

3.2 Categories of biostimulants

Du Jardin (2015) proposed eight categories: humic and fulvic acids, complex organic materials, beneficial chemical elements, inorganic salts (notably phosphite), seaweed extracts, chitin and chitosan derivatives, antitranspirants, and free amino acids and other nitrogenous compounds. Subsequent reviews (Rouphael & Colla, 2020) consolidated these into two broad classes: non-microbial biostimulants (humic substances, seaweed extracts, protein hydrolysates, chitosan and silicon) and microbial biostimulants (notably arbuscular mycorrhizal fungi and genera such as Rhizobium, Azotobacter and Azospirillum, the three bacterial genera explicitly permitted under EU Regulation 2019/1009). Humic substances activate plasma-membrane H+-ATPase activity, promote root elongation and improve micronutrient solubility (Canellas et al., 2015). Seaweed extracts, primarily from Ascophyllum nodosum and Ecklonia maxima, contain cytokinin-like and auxin-like compounds, betaines and polysaccharides that modulate gene expression and hormonal status (Battacharyya et al., 2015). Protein hydrolysates derived from animal or plant residues supply bioactive peptides and free amino acids that influence carbon and nitrogen metabolism (Colla et al., 2015). Figure 3 shows the global market composition and growth.

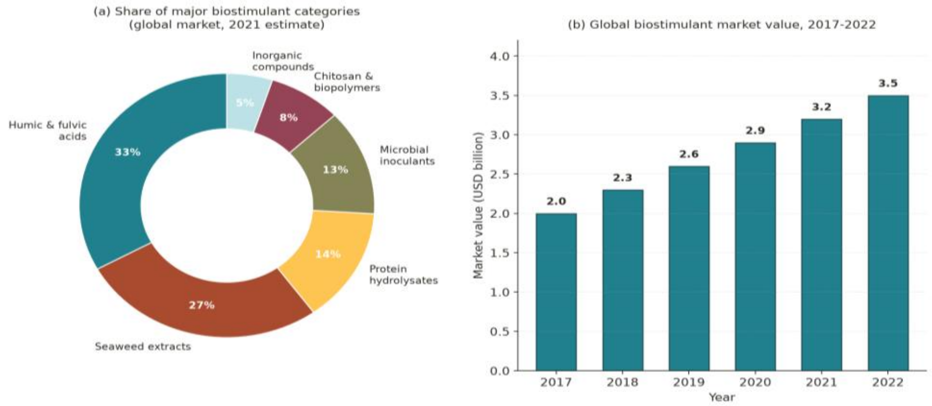

Figure3. Composition and market value of the global plant biostimulant industry

3.3 Modes of action

Although the molecular targets of many biostimulants remain only partially characterized, three convergent modes of action have been documented (Yakhin et al., 2017). First, biostimulants modulate phytohormone signaling, for example by supplying or eliciting auxin-, cytokinin- and gibberellin-like activities that influence root architecture and shoot growth. Second, they enhance primary and secondary metabolism by activating enzymes of nitrogen assimilation (e.g., glutamine synthetase, nitrate reductase) and by stimulating phenolic and flavonoid biosynthesis, which improves crop quality. Third, they prime plants for tolerance to abiotic stresses such as drought, salinity and heat by upregulating reactive-oxygen-species (ROS) scavenging systems, accumulating osmoprotectants such as proline and glycine betaine, and stabilizing photosynthetic machinery (Bulgari et al., 2019).

3.4 Agronomic performance

Multi-site studies confirm consistent though crop- and dose-dependent benefits. Foliar application of Ascophyllum nodosum extract increased tomato fruit yield by 12–24% and improved soluble solids content under Mediterranean conditions (Rouphael & Colla, 2020). Protein-hydrolysate biostimulants improved nitrogen-use efficiency in lettuce and spinach by 10–30% in greenhouse experiments (Colla et al., 2015). Humic acids applied at 50–100 mg L-1 increased maize root biomass by 20–37% over multiple field seasons (Canellas et al., 2015). Microbial biostimulants based on AM fungi and PGPR generally enhanced yield by 5–20% in cereals, oilseeds and vegetables, with the largest relative gains in soils with low organic matter or under moderate stress (Rouphael & Colla, 2020).

4. Integrated Role in Sustainable Crop Production

Biofertilizers and biostimulants are increasingly used in combination, and their effects can be additive or synergistic. Joint application of Rhizobium with AM fungi in legumes consistently outperforms either inoculant alone, owing to improved phosphorus supply to the nitrogen-fixing nodules (Mahanty et al., 2017). Seaweed extracts and humic acids enhance microbial colonization of roots, indirectly amplifying biofertilizer performance. From a systems perspective, these inputs reduce dependence on synthetic fertilizers, lower the carbon and nitrogen footprints of agriculture, restore soil microbial diversity and stabilize yields under climate variability (FAO, 2021). Figure 4 summarizes their integrated contribution to sustainable crop production.

A growing body of evidence indicates that the largest gains from integration are realized in degraded soils and stress-prone agro-ecologies, where mineral fertilizers alone fail to deliver consistent yields. In rainfed semi-arid regions of India and sub-Saharan Africa, combined applications of Rhizobium with AM fungi and seaweed-based biostimulants have raised legume yields by 25–40% over farmer practice (Mahanty et al., 2017). In Brazilian no-till systems, the co-use of Azospirillum brasilense with humic substances has improved maize and wheat nitrogen-use efficiency by approximately 15–20%, supporting the substitution of one-third of mineral nitrogen without yield penalty (Hungria et al., 2010). Such system-level benefits align with the United Nations Sustainable Development Goals, particularly SDG 2 (zero hunger), SDG 12 (responsible production) and SDG 13 (climate action), reinforcing the strategic role of these inputs in policy frameworks (FAO, 2021).

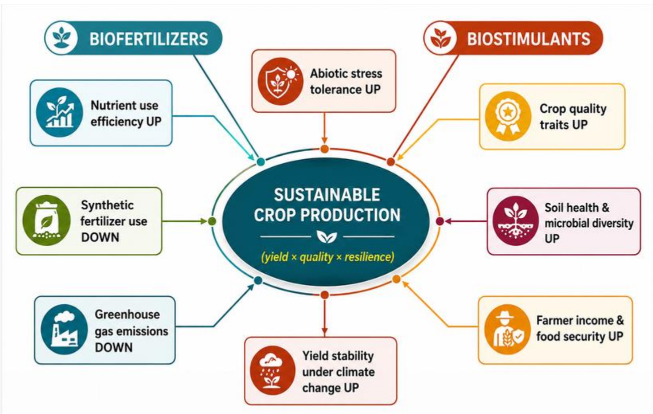

Figure4. Integrated contribution of biofertilizers and biostimulants to sustainable crop production

5. Commercial Status and Regulatory Landscape

The global biofertilizer market was estimated at USD 2.3 billion in 2021 with a projected compound annual growth rate of 12.1% through 2026, while the plant biostimulant market was valued at approximately USD 3.2 billion in 2021 and expected to surpass USD 5 billion by 2026 (Markets & Markets, 2022). India, China, Brazil and the United States are the largest producers of biofertilizer inoculants, while the European Union dominates biostimulant innovation. Regulatory frameworks have matured rapidly. The EU Fertilising Products Regulation 2019/1009, applicable from July 2022, harmonized definitions and CE-marking requirements, restricting microbial biostimulants to the four taxa Azotobacter, Azospirillum, Rhizobium and mycorrhizal fungi (European Parliament and Council, 2019). India amended its Fertilizer (Control) Order in 2021 to formally categorize biostimulants, while the United States Department of Agriculture and Environmental Protection Agency continue to develop a coordinated framework following the 2018 Farm Bill definition.

6. Challenges and Constraints

Despite encouraging results, several barriers constrain wider adoption. Inoculant quality is variable; surveys in India and Brazil have shown that 30–60% of commercial biofertilizer products contain fewer viable cells than declared on the label (Bhardwaj et al., 2014). Formulation stability under tropical storage temperatures remains a technical bottleneck. Field responses are influenced by indigenous microbial populations, soil pH, organic matter and irrigation regimes, leading to inconsistent performance across sites (Vejan et al., 2016). Biostimulants face an additional challenge of mechanism characterization: regulators increasingly demand documented modes of action, but many products are complex mixtures whose active components are not fully identified (Yakhin et al., 2017). Finally, farmer awareness, extension support and supply-chain logistics for live microbial products remain limited in many developing economies.

7. Emerging Trends

Three trends are reshaping the field. First, omics-guided design of microbial consortia uses metagenomics, transcriptomics and metabolomics to assemble multi-strain inoculants whose members occupy complementary functional niches, outperforming single-strain products under variable field conditions (Backer et al., 2018). Second, nano-formulations and encapsulation technologies (alginate, polymeric micro-beads, mesoporous silica) extend shelf life, enable controlled release and protect inoculants from desiccation and ultraviolet radiation. Third, precision agriculture is being coupled with biological inputs through sensor-based diagnostics, drone- or seed-coating delivery, and decision-support tools that match product, dose and timing to specific soil-crop combinations. These innovations, combined with maturing regulatory frameworks, are expected to lift adoption from below 5% of the global fertilizer market in 2022 toward a more substantial share over the coming decade (Markets & Markets, 2022).

Beyond formulation chemistry, the next decade is likely to witness convergence with digital agriculture and the circular bioeconomy. Sensor networks, hyperspectral imaging and machine-learning models can identify zones of nutrient deficiency or biotic stress at sub-field scale and trigger site-specific application of biofertilizers or biostimulants, reducing input volumes while maximizing response. The recovery of biostimulant ingredients from agro-industrial residues such as fish processing waste, animal blood, oilseed meals and seaweed cultivation by-products contributes to a circular bioeconomy by valorizing materials that would otherwise be discarded (Colla et al., 2015). In parallel, public research institutions in India, Brazil and the European Union have established quality-assurance laboratories and accredited testing protocols to certify cell counts, viability and efficacy, addressing one of the long-standing weaknesses of the commercial sector (Bhardwaj et al., 2014). Integration with cover cropping, conservation tillage and organic amendments further multiplies the agro-ecological benefits of these biological inputs.

CONCLUSION

Biofertilizers and biostimulants represent two complementary biological strategies for moving crop production toward greater sustainability. Biofertilizers contribute primarily through enhanced supply of nitrogen, phosphorus, potassium and micronutrients via living microbes that fix, solubilize or mobilize these elements. Biostimulants improve nutrient use efficiency, abiotic stress tolerance and crop quality through hormonal, metabolic and stress-protective mechanisms that operate independently of nutrient content. The literature published up to 2022 demonstrates that both inputs can reliably increase yields by 5–30% and reduce mineral fertilizer requirements by 20–50% across a range of crops and agro-ecologies, particularly under nutrient-limited or stress conditions. To realize their full potential, the field must overcome formulation, quality-control and regulatory bottlenecks, and embrace omics-based design, advanced delivery technologies and integration with precision farming. With these advances, biofertilizers and biostimulants are poised to become indispensable components of climate-resilient, low-input and ecologically sound agriculture.

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