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Advances in Biofertilizers and Biostimulants for Enhancing Agricultural Productivity and Soil Health

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ABSTRACT

Biofertilizers and biostimulants have emerged as sustainable alternatives to synthetic agrochemicals, offering significant potential to improve agricultural productivity while maintaining soil health. These eco-friendly inputs enhance nutrient availability, stimulate plant growth, improve stress tolerance, and promote beneficial microbial activity in the rhizosphere. Advances in microbial inoculants, seaweed extracts, humic substances, protein hydrolysates, and plant growth-promoting microorganisms have expanded their applications across diverse cropping systems. Their integration into climate-smart and precision agriculture supports improved crop yield, resource-use efficiency, and environmental sustainability. This review highlights recent innovations, mechanisms of action, practical applications, challenges, and future prospects of biofertilizers and biostimulants in sustainable agriculture.

Keywords: *Biofertilizer; biostimulant; plant growth-promoting rhizobacteria; soil health; sustainable agriculture.*

INTRODUCTION

Global agriculture faces the twin challenge of feeding a rapidly expanding human population, projected to cross 9 billion by 2050, while simultaneously protecting the natural resource base on which food production depends (FAO, 2017). Decades of Green Revolution technologies have delivered impressive gains in cereal productivity, but have also driven a heavy reliance on synthetic nitrogen, phosphorus and potassium fertilizers. Excessive use of these chemical inputs has been linked to declining fertilizer response ratios, groundwater contamination with nitrates, eutrophication of surface waters, greenhouse gas emissions and progressive depletion of soil organic carbon (Tilman et al., 2011; & Savci, 2012). Bhardwaj et al. (2014) reported that nitrogen use efficiency in Indian cereal systems has fallen to nearly 30–40 %, indicating that a substantial fraction of applied nutrients is lost to the environment. In this context, biofertilizers and plant biostimulants have emerged as central pillars of a more sustainable, low-input agriculture.

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Vessey (2003) defined a biofertilizer as a substance containing living microorganisms that, when applied to seeds, 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. Biostimulants, by contrast, are substances or microorganisms whose function, when applied to plants, is to stimulate natural processes to enhance nutrient uptake, nutrient use efficiency, tolerance to abiotic stress or crop quality traits, independently of their nutrient content (du Jardin, 2015).

The global biofertilizer market was valued at approximately USD 1.9 billion in 2020 and was projected to grow at nearly 12 % per year, while the biostimulant market crossed USD 2.6 billion in the same year (Rouphael & Colla, 2020). Their attractiveness stems from multiple benefits: reduced dependence on synthetic fertilizers, improved soil biological activity, lower input costs for smallholders and compatibility with organic and integrated nutrient management systems. Mahdi et al. (2010) emphasized that even a partial substitution of chemical fertilizers with biofertilizers can restore soil microbial diversity and enhance the sustainability of crop production.

2. Classification and Diversity of Biofertilizers

Biofertilizers are broadly grouped according to the primary nutrient they mobilize and the type of microorganism involved. Vessey (2003) and Bhardwaj et al. (2014) recognized four functional categories: nitrogen fixers, phosphate solubilizers and mobilizers, potassium and zinc solubilizers, and general plant growth promoters. Figure 1 summarizes this classification with representative genera.

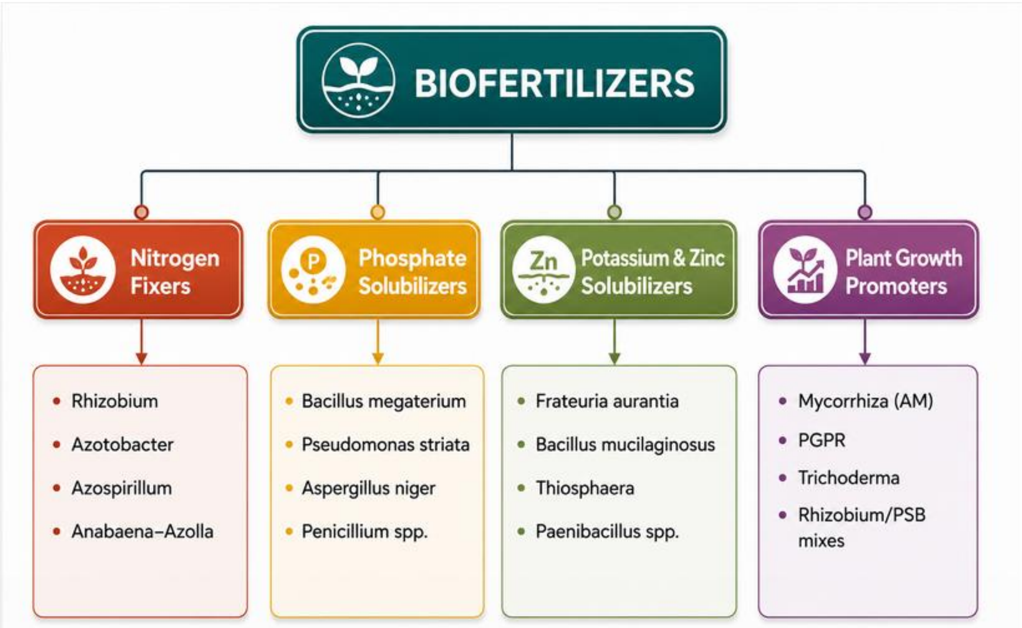

Figure1. Classification of biofertilizers based on function and microbial group

2.1 Nitrogen-fixing biofertilizers

Nitrogen fixers convert atmospheric dinitrogen into ammonia through the action of the nitrogenase enzyme complex. Symbiotic fixers such as Rhizobium, Bradyrhizobium and Frankia form nodules on legume and actinorhizal roots and can fix 50–300 kg N ha^{-1} per season under favourable conditions (Peoples et al., 2009). Free-living and associative fixers such as Azotobacter, Azospirillum, Herbaspirillum and Acetobacter diazotrophicus contribute significantly to non-legume systems including cereals, sugarcane and grasses (Baldani & Baldani, 2005). Cyanobacterial biofertilizers, particularly the Anabaena–Azolla symbiosis, remain an important source of nitrogen for lowland rice, adding 20–40 kg N ha^{-1} under Indian conditions (Singh et al., 2016).

2.2 Phosphate-solubilizing and mobilizing biofertilizers

A large fraction of soil phosphorus is present in unavailable forms bound to calcium, iron or aluminium. Phosphate-solubilizing microorganisms (PSM), including Bacillus megaterium, Pseudomonas striata, Aspergillus niger and Penicillium species, produce low-molecular-weight organic acids such as gluconic, citric and oxalic acid that release inorganic P from insoluble minerals (Khan et al., 2009). Arbuscular mycorrhizal fungi (AMF) act as phosphate mobilizers by extending their hyphal network far beyond the root depletion zone; Smith and Read (2008) reported that AMF can deliver up to 80 % of the P and 25 % of the N acquired by host plants.

2.3 Potassium, zinc and other micronutrient solubilizers

Frateuria aurantia, Bacillus mucilaginosus and Thiobacillus ferrooxidans are among the microorganisms capable of releasing potassium from insoluble minerals such as mica, feldspar and orthoclase (Meena et al., 2015). Zinc-solubilizing bacteria including Pseudomonas fluorescens and Bacillus subtilis convert insoluble zinc compounds into plant-available forms, thereby correcting one of the most widespread micronutrient deficiencies in Indian soils (Sharma et al., 2013). Iron-mobilizing rhizobacteria produce siderophores that chelate ferric iron and facilitate its uptake in calcareous soils (Ahemad & Kibret, 2014).

2.4 Plant growth-promoting rhizobacteria (PGPR) and endophytes

PGPR such as Pseudomonas fluorescens, Bacillus subtilis and Azospirillum brasilense promote plant growth through both direct and indirect mechanisms. Direct effects include the synthesis of indole-3-acetic acid (IAA), gibberellins, cytokinins and 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which reduces ethylene-mediated stress (Glick, 2012). Indirect effects include the production of siderophores, hydrogen cyanide, chitinolytic enzymes and antibiotics that suppress soil-borne pathogens. Endophytic microorganisms such as Piriformospora indica further enhance root architecture, nutrient uptake and abiotic stress tolerance in a wide range of crops (Varma et al., 2012).

3. Categories and Mechanisms of Plant Biostimulants

du Jardin (2015) classified plant biostimulants into seven categories: humic and fulvic acids, protein hydrolysates and amino acids, seaweed extracts, chitosan and biopolymers, inorganic compounds, beneficial fungi and beneficial bacteria. Figure 3 depicts their approximate share in the global market in 2020, based on Rouphael and Colla (2020).

3.1 Humic and fulvic substances

Humic and fulvic acids are complex polymers derived from decomposed organic matter, leonardite or vermicompost. They improve soil cation exchange capacity, chelate micronutrients and stimulate the activity of the plasma-membrane H^+-ATPase, thereby enhancing nutrient uptake (Canellas & Olivares, 2014). Foliar or soil application of humic acids has been shown to increase root biomass, chlorophyll content and yield in maize, tomato and wheat (Nardi et al., 2016).

3.2 Seaweed extracts and botanicals

Extracts of brown algae, particularly Ascophyllum nodosum, Ecklonia maxima and Sargassum species, contain phytohormones (auxins, cytokinins, gibberellins), betaines and polysaccharides such as alginates and fucoidans. Craigie (2011) reported that seaweed extracts promote root growth, delay senescence, and improve tolerance to drought, salinity and cold. Field trials on horticultural crops have documented yield increases of 10–30 % following foliar sprays of seaweed formulations (Battacharyya et al., 2015).

3.3 Protein hydrolysates and amino acid formulations

Protein hydrolysates produced by enzymatic or chemical hydrolysis of plant and animal proteins contain free amino acids, peptides and low-molecular-weight nitrogenous compounds. They act as signalling molecules that stimulate nitrogen metabolism, hormonal balance and root proliferation (Colla et al., 2015). Their beneficial effects have been demonstrated in leafy vegetables, fruit crops and cereals under both optimal and stress conditions.

3.4 Chitosan, biopolymers and inorganic biostimulants

Chitosan, a deacetylated derivative of chitin, elicits plant defence responses through the induction of pathogenesis-related proteins and phytoalexins (Pichyangkura & Chadchawan, 2015). Beneficial inorganic elements such as silicon, selenium and cobalt act as biostimulants at low concentrations by strengthening cell walls, scavenging reactive oxygen species and improving stress tolerance (du Jardin, 2015).

3.5 Microbial biostimulants

Beneficial fungi such as arbuscular mycorrhizae and Trichoderma harzianum, together with PGPR like Bacillus and Pseudomonas, are increasingly formulated as biostimulants because their effects go beyond simple nutrient supply. They modulate root architecture, induce systemic resistance and improve tolerance to drought and salinity (López-Bucio et al., 2015).

4. Mechanisms of Action

Biofertilizers and biostimulants act through several complementary mechanisms in the rhizosphere, illustrated in Figure 2. First, they enhance nutrient acquisition by biological nitrogen fixation, solubilization of insoluble P and K compounds, and mineralization of organic nutrient reserves (Bhardwaj et al., 2014). Second, they modulate plant physiology through the synthesis of phytohormones such as IAA, gibberellins and cytokinins, and through ACC-deaminase activity that lowers stress ethylene (Glick, 2012). Third, they improve soil physical and biological quality by producing extracellular polymeric substances that stabilize aggregates, increase water-holding capacity and stimulate the activity of native microflora and mesofauna (Rashid et al., 2016).

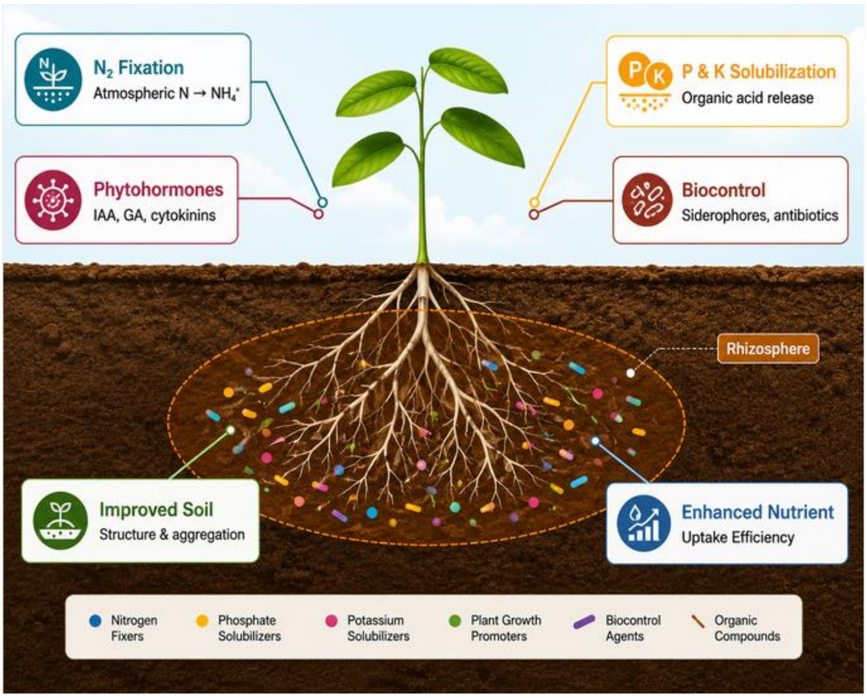

Figure2. Mechanisms of biofertilizer and biostimulant action in the rhizosphere

Fourth, several biofertilizer strains produce siderophores, hydrogen cyanide, antibiotics and lytic enzymes that suppress plant pathogens, thereby acting as biocontrol agents (Ahemad & Kibret, 2014). Fifth, biostimulants specifically upregulate genes involved in nutrient transport, antioxidant defence and osmotic adjustment, priming plants to cope with abiotic stresses such as drought, salinity and heat (Van Oosten et al., 2017).

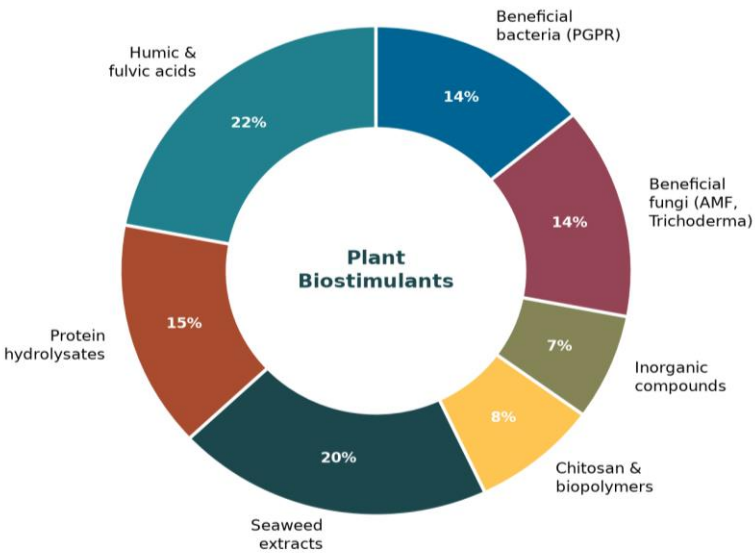

Figure3. Major categories of plant biostimulants and their approximate market share (2020)

5. Effects on Crop Productivity and Soil Health

A large body of field and pot experiments has documented the positive effects of biofertilizer and biostimulant application on crop productivity across cereals, pulses, oilseeds and vegetables. A meta-analysis by Schütz et al. (2018) covering 171 field trials reported an average yield gain of 16 % when PGPR were applied to major crops, with the largest responses in low-input and rainfed systems. Basu et al. (2021) similarly synthesized evidence showing consistent yield improvements of 10–30 % with the use of nitrogen-fixing and phosphate-solubilizing microorganisms. Figure 4 summarizes representative yield improvements compiled from Indian and international studies published up to 2021.

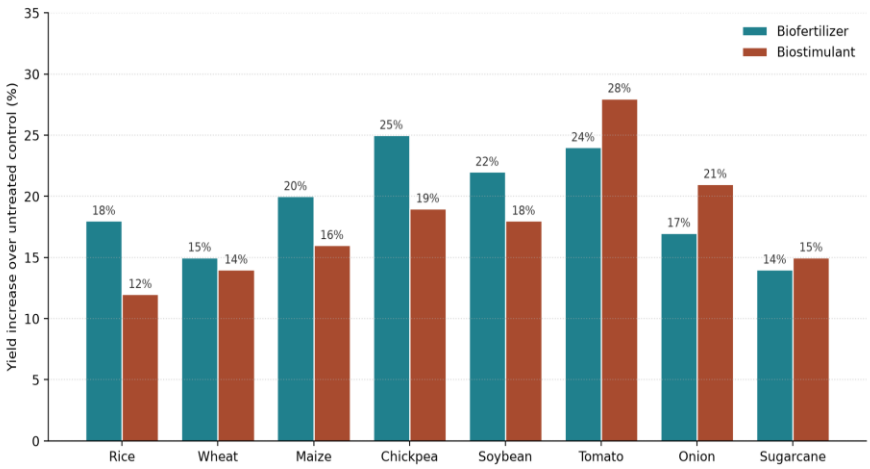

Figure4. Reported yield improvement (%) with biofertilizer and biostimulant application across major crops

Beyond yield, these inputs contribute substantially to soil health. Long-term studies at the Indian Council of Agricultural Research (ICAR) network have shown that combined application of Rhizobium, PSM and AMF with reduced chemical fertilization improved soil organic carbon by 15–25 %, microbial biomass carbon by 30–40 %, and dehydrogenase activity by up to 60 % compared with sole chemical fertilization (Mahdi et al., 2010). Rashid et al. (2016) reported that PGPR-based inoculants enhanced soil aggregate stability and porosity, thereby improving infiltration and reducing runoff.

Biostimulants complement these effects by improving crop quality. Rouphael and Colla (2020) demonstrated that foliar application of protein hydrolysates and seaweed extracts increased fruit firmness, soluble solids and antioxidant content in tomato, pepper and strawberry. In cereals, humic-acid-based products enhanced grain protein content and micronutrient density, contributing to nutritional security.

6. Formulation, Delivery and Quality Considerations

The efficacy of biofertilizers and microbial biostimulants depends critically on the number of viable propagules delivered to the plant, their shelf life and their ability to colonize the rhizosphere. Traditional carriers such as lignite, peat, charcoal and vermiculite have been progressively replaced by liquid formulations that offer higher cell counts, longer shelf life and easier application (Bashan et al., 2014). Encapsulation of microbial cells in alginate or starch beads and the use of nanocarriers has further improved survival under storage and field conditions (Malusá et al., 2012).

Consortium-based formulations combining nitrogen fixers, phosphate solubilizers, PGPR and mycorrhizae have shown synergistic effects that exceed those of single-strain inoculants (Nadeem et al., 2014). However, quality control remains a major concern. Herrmann and Lesueur (2013) surveyed commercial products in several countries and found that a large proportion did not contain the declared microbial strains at effective concentrations, underlining the need for stringent regulatory standards and independent quality certification.

7. Constraints and Future Outlook

Despite their proven benefits, the adoption of biofertilizers and biostimulants remains uneven. Key constraints identified up to 2021 include: variability of field performance due to soil and climatic factors; poor product quality and short shelf life; limited farmer awareness and technical support; inadequate regulatory frameworks in many developing countries; and the absence of standardized protocols for testing bioefficacy (Bhardwaj et al., 2014; & Ricci et al., 2019).

Emerging research directions include the design of climate-smart microbial consortia targeted at drought- and salinity-affected soils, integration of biofertilizers with precision nutrient management guided by decision-support systems, and application of omics tools to identify novel plant-microbe interactions (Basu et al., 2021). The convergence of nanotechnology, synthetic biology and microbial ecology is expected to yield next-generation formulations that are more predictable and site-specific.

CONCLUSION

Biofertilizers and biostimulants have moved from the periphery to the mainstream of modern crop production. Evidence accumulated up to 2021 clearly shows that they can enhance nutrient use efficiency, improve crop yield and quality by 10–30 % across a wide range of crops, and simultaneously restore soil biological health. Their integration into nutrient management programmes offers a realistic pathway to reduce dependence on chemical fertilizers, mitigate environmental externalities and build resilience against climate variability. Realizing this potential, however, requires strong quality regulation, robust extension support and continued research into strain selection, formulation stability and multi-strain consortia. As demonstrated by Vessey (2003), Bhardwaj et al. (2014), du Jardin (2015), Rouphael and Colla (2020) and Basu et al. (2021), biofertilizers and biostimulants together constitute an indispensable component of the transition towards sustainable, climate-smart and productive agriculture.

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Author Contribution:

Both author have participated in critically revising of the entire manuscript and approval of the final manuscript.

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