



## Biostimulants and Bharat's Bio-Revolution: Decoding the Soil-Genome Dialogue

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With climate change threatening global agriculture and projected to cause a 21% slowdown in productivity growth since 1961 due to environmental stresses, the search for sustainable solutions has intensified (Meena *et al.*, 2025). Against this backdrop, biostimulants have emerged as transformative agents in the agricultural landscape. Unlike conventional fertilizers that directly supply nutrients, these biological catalysts operate through sophisticated mechanisms: enhancing nutrient efficiency, fortifying stress tolerance, and activating plant innate immunity. The European Union's Fertilising Products Regulation (2019/1009) formally defines them as "*products stimulating plant nutritional processes independently of their nutrient content*". With the biostimulant market projected to grow at 10.5% annually, reaching USD 6 billion by 2030, their integration into farming systems signifies a paradigm shift toward ecological practices resilience. For India, where 147 million hectares suffer degradation and rainfed agriculture dominates, biostimulants provide a scientifically supported way to rejuvenate soils and ensure yields amid climatic chaos (Bhupenchandra *et al.*, 2022).

### Decoding Biostimulants: Beyond Fertilizers and Pesticides

**Historical Context and Scientific Evolution:** The use of growth-enhancing substances traces back centuries, coastal communities applied seaweed extracts long before their scientific validation in the 19th century. However, the term "biostimulant" entered the scientific lexicon only in the late 20th century, when researchers began distinguishing these materials from fertilisers and pesticides based on their mode of action. Virginia Tech scientists initially defined them as "*compounds stimulating plant growth in minute quantities*," emphasizing their non-nutritional role (Garg *et al.*, 2024). This conceptual evolution culminated in the EU's 2019 regulatory framework, which recognized biostimulants as tools for enhancing: Nutrient use efficiency, abiotic stress tolerance, soil nutrient bioavailability and crop quality traits.

**Classification and Functional Diversity:** Biostimulants fall into microbial and non-microbial categories, each with distinct functional mechanisms:

**Table 1: Biostimulant Classification and Primary Functions**

Category	Examples	Key Functions
Microbial	PGPR ( <i>Azospirillum</i> , <i>Rhizobia</i> ), Mycorrhizal fungi, <i>Trichoderma</i>	Nitrogen fixation, phosphate solubilization, phytohormone production, induced systemic resistance
Non-Microbial	Seaweed extracts, Humic substances, Protein hydrolysates, Plant-derived antioxidants	Enhanced root architecture, ROS scavenging, osmotic adjustment, nutrient chelation
Combined	Microbial consortia with organic carriers	Synergistic enhancement of soil fertility and stress resilience

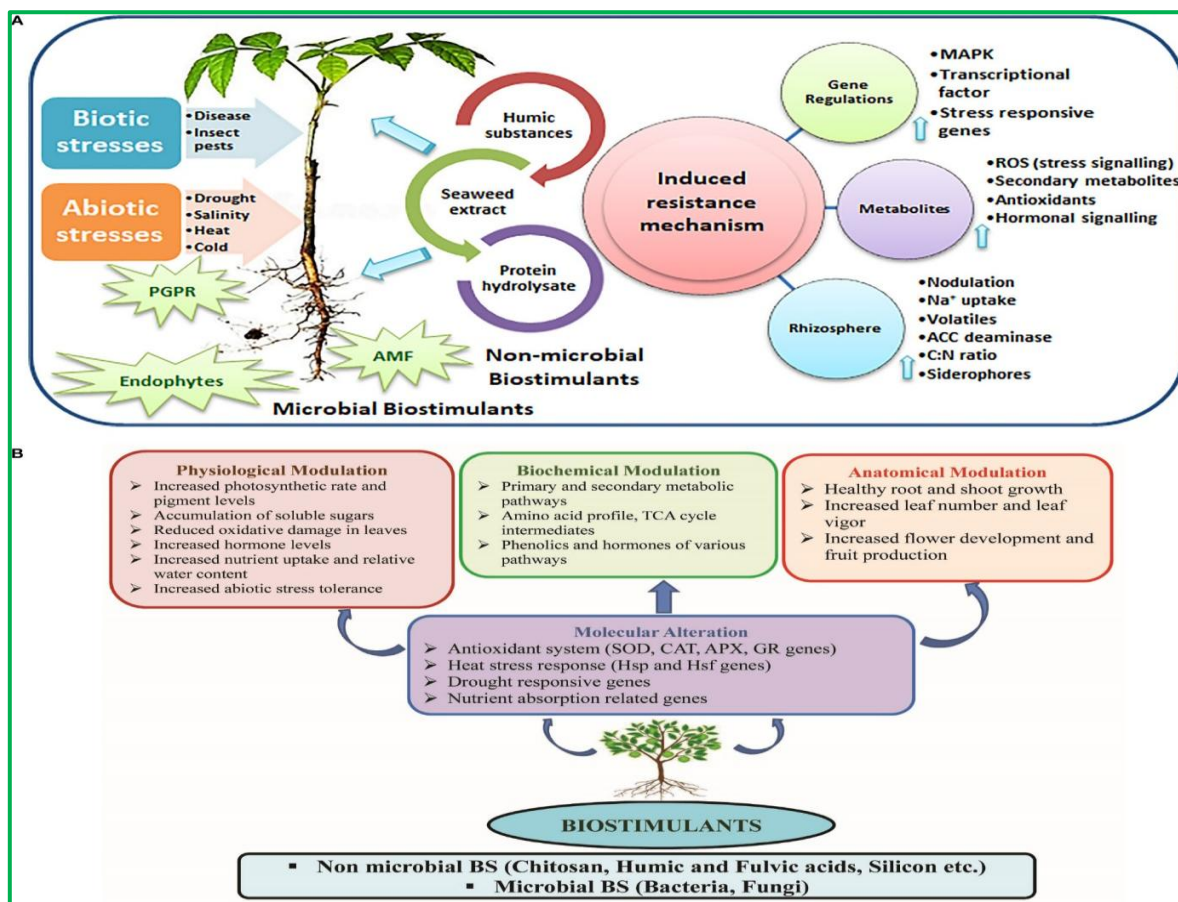
Microbial inoculants, especially Plant Growth-Promoting Rhizobacteria (PGPR), lead research, representing 37% of biostimulant studies (Garg *et al.*, 2024). For instance, *Rhizobia* spp. boost nitrogen availability in legumes, while *Pseudomonas* solubilizes phosphorus, increasing uptake efficiency by 30–50% (Bhupenchandra *et al.*, 2022). Non-microbial agents like *Ascophyllum nodosum* seaweed extracts contain bioactive compounds (e.g., betaines, mannitol) that prime plants against drought and salinity.

## The Genomic Orchestra: How Biostimulants Work

**Molecular Mechanisms Unveiled:** Biostimulants act as "molecular translators" between plants and their environment. At the cellular level, they trigger cascades of physiological adjustments:

- **Antioxidant Activation:** Under drought or salinity stress, biostimulants upregulate enzymes such as superoxide dismutase (SOD) and catalase (CAT), thereby neutralising reactive oxygen species (ROS) that cause cellular damage. Melatonin-based biostimulants elevate proline synthesis in maize, improving water retention during drought (Bhupenchandra *et al.*, 2022).
- **Phytohormone Mimicry:** Humic substances mimic auxins, stimulating root proliferation and increasing nutrient foraging capacity by up to 70% (Khoulati *et al.*, 2025).
- **Osmotic Engineering:** Compounds like glycine betaine accumulate in cells, maintaining turgor pressure under water stress. In tomatoes, betaine applications reduce yield losses by 40% during drought events (Bhupenchandra *et al.*, 2022).

**Soil Microbiome Remodeling:** Biostimulants reconfigure rhizosphere communities, enriching beneficial taxa that support plant health. A landmark 2023 study using 16S rRNA sequencing across Brazilian and Paraguayan farms revealed that *Prevotella* (cotton), *Methylocapsa* (sugarcane), and *Rhizophlyctis* (corn) proliferate in biostimulant-treated soils, enhancing nitrogen cycling and disease suppression. This microbiome shift is linked to a 0.84 impact index on soil biology, the highest among sustainability indicators (Mendes *et al.*, 2023).



**Figure 1: Biostimulant Action at Molecular and Ecosystem Levels**

Genomic Insights: Biostimulants Meet Omics Technologies

**Decoding Stress Responses:** Next-generation sequencing has illuminated how biostimulants fundamentally rewire plant genomes at the molecular level, revealing intricate stress-adaptation mechanisms previously hidden from science. When *Glomus caledonium*, a mycorrhizal fungus, colonizes maize roots, it triggers a cascade of genomic responses: a dramatic 15-fold increase in *Bt* toxin gene expression enhances insect resistance while simultaneous upregulation of salicylic acid biosynthesis genes primes systemic defenses against pathogens. Concurrently, these symbiotic interactions stimulate enhanced silica deposition in cell walls, physically fortifying plants against environmental assaults. Similarly, advanced nanopore sequencing of biostimulant-treated crops exposed to drought has uncovered the differential expression of aquaporin genes, critical molecular gatekeepers that regulate water channel efficiency. This genomic reprogramming allows plants to optimize hydraulic conductivity under moisture stress, effectively transforming cellular architecture into a more resilient framework (Garg *et al.*, 2024).

**Microbial Dark Matter Explored:** Microbial dark matter has long been a mystery in biostimulant science, as less than 1% of soil microbes are culturable, creating a "black box" of unexplored microbial potential (Mendes *et al.*, 2023). However, advancements in shotgun metagenomics are now allowing scientists to link uncultured taxa with specific functions. For instance, nanoball sequencing has revealed the presence of *Candidatus Nitrosocosmicus*, an archaeon that is capable of fixing atmospheric nitrogen in humic acid-amended soils, even without the need for oxygen (Garg *et al.*, 2024). Additionally, machine learning algorithms are being used to predict microbial interactions, which enables the design of synthetic consortia. One example of this innovation is the use of *Trichoderma* and cyanobacteria blends, which have been shown to increase rice yields by 22% in saline soils.

Herbaria Genomics: Climate Adaptation Blueprints:

UC Berkeley researchers have uncovered “historical adaptation strategies” by sequencing herbarium specimens of *Arabidopsis thaliana* dating back 250 years. Stomatal density genes responsive to rising CO<sub>2</sub> levels provide templates for engineering climate-resilient crops, an approach now being applied to staple Indian crops like rice wheat.

Agricultural Applications: From Labs to Fields

**Quantifying Agronomic Benefits:** India's agricultural landscape—characterized by monsoon dependency (67% of cultivated area), degraded soils (147 million hectares), and smallholder dominance (138 million farmers averaging 1.15 ha)—has emerged as a testing ground for biostimulants. Field data from ICAR trials, state agricultural universities, and industry reports reveal transformative agronomic gains across key crops and soil types.

Table 2: State-Wise Biostimulant Impact on Major Crops (2023–2024)

State	Crop	Biostimulant Type	Key Impact	Yield Increase
Punjab	Rice-Wheat	Seaweed extracts	20% N reduction, 25% yield rise	5.2 → 6.5 tons/ha
Maharashtra	Mango	Humic acids	40% fruit retention under heat stress	8 → 11 tons/ha
Uttar Pradesh	Sugarcane	<i>Kappaphycus</i> liquid	12% tonnage, +2.0 sucrose units	75 → 84 tons/ha
Karnataka	Finger Millet	PGPR consortia	28% faster maturity, 32% grain weight	1.1 → 1.45 tons/ha
Gujarat	Cotton	Amino acid formulations	25% less boll shedding, 18% fiber strength	550 → 650 kg/ha

Source: Compiled from ICAR-CRIDA reports, BIPA field data (2025), and industry trials. (Reddy, 2025)

Climate Resilience Amplified

Biostimulants play a crucial role in mitigating the vulnerabilities of agriculture to climate change. For example, wheat primed with sodium silicate exhibited a remarkable 50% improvement in water retention, enabling the crop to sustain yields at 80% of optimal irrigation levels even during drought conditions. In response to salinity, seaweed extracts

have proven effective in reducing NaCl uptake in lettuce by chelating sodium ions, which led to a 32% increase in marketable yield. Additionally, biostimulants such as protein hydrolysates have helped preserve pollen viability in tomatoes under extreme heat conditions, specifically at 42°C, preventing fruit abortion and thus ensuring crop productivity. Moreover, biostimulants contribute to reducing agriculture's climate footprint. For instance, the application of *Kappaphycus* seaweed extract resulted in a significant reduction of greenhouse gas emissions, cutting down by 260 kg CO<sub>2</sub>e per ton of sugarcane produced. This not only showcases their potential to enhance crop resilience but also highlights their role in fostering more sustainable agricultural practices (Bhupenchandra *et al.*, 2022).

### Challenges and Future Trajectories

Biostimulants face significant hurdles in India, including regulatory fragmentation where classifications like *Azotobacter* oscillate between "biofertilizer" and "biostimulant" across states, stifling pan-Indian standardization and trade; product inconsistency plagues the sector due to variable raw materials (e.g., divergent seaweed species or extraction methods), with only 12% of commercial products undergoing genomic quality assurance, causing erratic field efficacy; and economic barriers deter smallholders, as upfront costs (₹800–1,200/ha) clash with cash-flow constraints despite proven ROI of 3.5x via fertilizer savings (Khoulati *et al.*, 2025). Future trajectories aim to address these gaps through nano-biostimulants like chitosan-encapsulated *Bacillus* spores that cut application rates by 50% while improving drought resilience in rainfed crops (Khoulati *et al.*, 2025); AI-driven formulations utilizing India's soil health card data and crop phenomics to create location-specific microbial consortia, showing a 22% yield increase for salt-stressed rice in Tamil Nadu; and CRISPR-enhanced microbes, where gene-edited Rhizobia with increased *nifH* promoters achieve twice as fast nitrogen fixation, expected to replace urea in pulse cropping systems by 2030. Policy alignment remains critical—harmonizing state regulations with FCO 2021 amendments and subsidizing nano-scale biofactories through KVKs could unlock biostimulants' potential for 138 million smallholders (ICAR-CRIDA Policy Brief, 2025).

### Policy Imperatives for India

India's leadership in biostimulant research, ranking third globally in terms of publications, needs to be translated into practical field adoption. One of the strategic priorities is the establishment of unified standards. This involves aligning with the European Union's Fertilizers Product Regulation (FPR) 2019/1009 to create standardized testing protocols focused on microbial function rather than taxonomic identity. Additionally, there is a need for subsidies aimed at supporting biofactories, particularly decentralized units that produce cost-effective plant growth-promoting rhizobacteria (PGPR) consortia. Leveraging India's extensive network of over 500 Krishi Vigyan Kendras (KVKs) could significantly boost the scale and reach of such initiatives (Bhupenchandra *et al.*, 2022). Another priority is the creation of genomic databases. Developing open-access repositories that catalog stress-responsive genes, such as *OsNAC9* in rice, would accelerate the development of new biostimulant products, enhancing their effectiveness in tackling environmental challenges faced by crops (Kumar *et al.*, 2024).

### Conclusion: The Roots of Tomorrow's Harvest

Biostimulants represent more than agricultural inputs—they are mediators of a genomic dialogue between plants and their environment. As research unravels their mechanisms through omics technologies, we advance toward precision bio-solutions that could reduce synthetic fertilizer use by 30% by 2030 (Khoulati *et al.*, 2025). For Indian agriculture, where degraded soils and climate vulnerability threaten food security, biostimulants offer a path to rejuvenate agroecosystems while sustaining yields. Initiatives like the Salk Institute's carbon-sequestration project engineering deeper-rooted crops using biostimulant-primed genomic insights—exemplify the transformative potential. As we stand at the convergence of genomics and ecology, biostimulants emerge not merely as tools, but as foundational

elements in reimagining agriculture's future—one where soil vitality and plant resilience jointly nourish our planet.

*“In the alchemy of soil and seed, biostimulants are the catalysts turning despair into harvest.”*

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