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The Green Revolution 2.0: Biostimulants for Enhanced Vegetable Quality and Shelf Life

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Plant biostimulants offer a sustainable solution for modern agriculture, optimizing plant's innate potential to enhance vegetable quality and post-harvest longevity while reducing synthetic input reliance. Pre-harvest applications improve nutritional and sensory attributes, while post-harvest treatments and carry-over effects extend shelf life. However, challenges include variable efficacy, regulatory uncertainty and the need for grower education. Despite this, the market is rapidly growing and maturing, driven by sustainability demands. Future advancements, like precision agriculture integration and advanced formulations, position biostimulants as a critical tool for climate-resilient and circular agricultural systems.

Introduction

Plant biostimulants represent a significant shift in modern agriculture, moving away from an input-centric model of direct nutrient supply or pest eradication towards an efficiency-centric model that optimizes a plant's innate biological potential. This innovative category of agricultural inputs helps address the dual challenge of increasing productivity for global food security while transitioning to more sustainable practices that mitigate environmental degradation caused by intensive synthetic chemical use. The global market for biostimulants, valued at approximately ₹195.24 billion in 2018, is projected to exceed ₹354.99 billion by 2025 and potentially reach ₹695.54 billion by 2030, reflecting increasing investment (Miron, 2015) and broad industry consensus on their importance.

Defining Plant Biostimulants

A plant biostimulant is widely understood as a product that stimulates natural plant nutrition processes independently of its own nutrient content (Ricci *et al.*, 2019), with the sole aim of improving one or more of the following characteristics: nutrient use efficiency, tolerance to abiotic stress and overall crop quality (Drobek *et al.*, 2019). This functional definition distinguishes biostimulants from conventional agricultural inputs.

Biostimulants differ from fertilizers and pesticides in their mode of action (Bulgari *et al.*, 2015). Unlike fertilizers, which supply essential nutrients, biostimulants enhance plants ability to acquire and utilize nutrients (Ricci *et al.*, 2019). They don't act as significant nutrient sources but rather stimulate plant processes. Biostimulants also differ from pesticides, which directly target pests or pathogens (Bulgari *et al.*, 2015). Instead, biostimulants promote plant health and vigor, indirectly improving resilience to stressors. They may trigger systemic resistance pathways, priming plants natural defenses (Pereira *et al.*, 2021). This distinction is crucial for regulatory purposes, as product claims determine classification as a biostimulant or pesticide.

Classification of Major Biostimulant Categories

Plant biostimulants are a diverse group, typically classified by their origin and composition. Key categories include:

- **Humic and Fulvic Acids (Humic Substances)**: These complex organic molecules, derived from decomposed plant, animal and microbial residues, improve soil structure, increase water retention and chelate nutrients for better plant uptake (Corsi *et al*., 2022).
- **Seaweed Extracts and Botanicals**: Obtained from marine macroalgae or terrestrial plants, these extracts contain bioactive compounds like polysaccharides, phytohormones, amino acids and vitamins, influencing hormone-like activity, osmotic adjustment and antioxidant defense (Li *et al*., 2022).
- **Protein Hydrolysates and Nitrogenous Compounds**: Mixtures of peptides and free amino acids from plant or animal sources, they stimulate nitrogen and carbon metabolism, serve as precursors for phytohormones and chelate micronutrients (Corsi *et al*., 2022).
- **Microbial Inoculants**: Microbial inoculants contain beneficial microorganisms like Plant Growth-Promoting Rhizobacteria (PGPR) and Arbuscular Mycorrhizal Fungi (AMF). These microbes enhance plant growth through nitrogen fixation, phosphate solubilization, phytohormone production and symbiotic relationships, improving nutrient uptake, soil structure and systemic resistance (Corsi *et al*., 2022).
- **Biopolymers and Other Compounds**: Diverse materials like chitosan (from crustacean shells), known for eliciting plant defense responses and antimicrobial activity and inorganic compounds like silicon salts that enhance structural integrity and stress tolerance (Li *et al*., 2022).

Core Mechanisms of Biostimulant Action in Plants

Biostimulants enhance plant growth, defense and nutrient management by modulating fundamental physiological and biochemical processes. A key concept is priming, where biostimulants prepare the plant to respond more rapidly and robustly to future challenges, building resilience. Their actions are multifaceted:

- **Modulation of Phytohormonal Balance and Signaling**: Many biostimulants, especially seaweed extracts and protein hydrolysates, contain or stimulate the plant's production of phytohormones like auxins, cytokinins and gibberellins. This fine-tunes plant growth, root development, cell division and stress-related hormonal responses.
- **Enhancement of Nutrient Uptake and Assimilation**: Biostimulants improve nutrition indirectly by conditioning the soil (e.g., humic substances improving soil structure and cation exchange capacity) and directly by enhancing the plant's ability to absorb and utilize nutrients. They can stimulate root growth, act as natural chelating agents for micronutrients and up-regulate genes for nutrient transporters and assimilation enzymes.
- **Activation of Antioxidant Defense Systems and Abiotic Stress Mitigation**: Biostimulants enhance plant tolerance to abiotic stresses like drought, salinity and extreme temperatures by activating antioxidant defense systems. They increase antioxidant enzyme activity and promote accumulation of non-enzymatic antioxidants and osmolytes, helping cells maintain water uptake and reducing stress damage. This boosts plant resilience.
- **Stimulation of Primary and Secondary Plant Metabolism**: Biostimulants can boost primary metabolism by increasing photosynthetic pigment concentration (e.g., chlorophyll) and the activity of photosynthetic enzymes. They also activate secondary metabolism pathways, leading to the accumulation of beneficial compounds like phenolics, flavonoids and anthocyanins, which contribute to the nutritional and organoleptic quality of vegetables.

Pre-Harvest Application: Enhancing Intrinsic Vegetable Quality

Applying biostimulants before harvest optimizes plant physiology, resulting in vegetables with superior nutritional profiles, enhanced sensory characteristics and improved physical attributes.

- **Fruit-Bearing Vegetables (Tomato, Pepper)**: Biostimulants significantly improved tomato yield and quality. Protein hydrolysates increased marketable yield (15.4%), fruit weight (19.8%) and lycopene content (34.9%). Seaweed extracts enhanced yield, carbohydrate content and fruit firmness, while reducing salinity-induced yield loss. Microbial inoculants boosted fruit weight, size and skin elasticity, with co-application with fulvic acid increasing phenolic and flavonoid content. These biostimulants improved tomato quality and nutritional value (Zhao *et al*., 2024).
- **Leafy Greens (Lettuce, Spinach, Kale)**: Biostimulants improved lettuce and spinach quality. Microbial inoculants increased head weight and reduced unmarketable leaves. They also boosted protein, vitamin C and phenols. Plant-derived extracts like *Moringa oleifera* increased soluble protein, carotenoids and chlorophyll. Protein hydrolysates increased marketable yield and antioxidant activity (Gruda *et al*., 2025).
- **Root and Tuber Vegetables (Potato, Carrot, Radish)**: Humic and Fulvic Acids (HFA) with PGPR increased potato yield by 140% and improved quality. HFA also enhanced sugar and carotenoid content in carrots. Amino acids and biostimulants improved radish quality, boosting phenolics, protein and ascorbic acid. These biostimulants significantly enhanced yield and nutritional value of root and tuber vegetables (Zhao *et al*., 2024).

Post-Harvest Performance: Extending Vegetable Shelf Life

Biostimulants extend shelf life and maintain quality post-harvest through carry-over effects, biocontrol of pathogens and direct treatments.

- **Carry-Over Effects of Pre-Harvest Treatments**: By enhancing plant resilience during growth, biostimulants produce vegetables with stronger cell wall structures, higher antioxidant reserves and delayed senescence. Pre-harvest humic and fulvic acids on tomatoes led to better firmness retention, lower weight loss (5.9%) and higher ascorbic acid and pectin during storage. Protein-based biostimulants improved visual quality and reduced browning in stored lettuce (Gruda *et al*., 2025).
- **Biocontrol of Post-Harvest Pathogens**: Microbial inoculants act as biocontrol agents by competing with pathogens for space, producing antimicrobial compounds and triggering the host's innate defense mechanisms. Through competition, antibiosis and induced resistance, they effectively control fungal and bacterial pathogens. For example, *Bacillus velezensis* WZ-37 reduced tomato decay by 33.3% after 21 days of storage, demonstrating their potential in post-harvest disease management (Gruda *et al*., 2025).
- **Biostimulants as Direct Post-Harvest Treatments**: Certain biostimulants form edible coatings that extend shelf life by acting as semi-permeable barriers. Chitosan coatings can extend tomato shelf life up to 30 days and inhibit spoilage fungi. Adding cinnamon oil to chitosan further enhances shelf life. Seaweed extract coatings also preserve tomato quality by reducing water loss and retaining texture and ascorbic acid.

Strategic Application for Optimal Efficacy

Effective biostimulant use requires strategic selection of product, application method, dosage and timing.

- **Application Methods**: Biostimulants can be applied through various methods, including foliar spray for rapid uptake of soluble compounds, soil drench or fertigation for root system interaction, seed treatment for early root colonization and in-furrow application for precise placement. Each method optimizes the effectiveness of different biostimulant types, such as protein hydrolysates, seaweed extracts, humic substances and microbial inoculants.
- **Dosage, Timing and Formulation**: Optimal dosage is crucial; too little may have no effect, too much can be phytotoxic. Timing should align with plant phenological stages (e.g., root growth promotion during seedling establishment, stress tolerance pre-stress event). Formulations (liquids, powders, granules) should match the chosen application method.

- **Synergistic Effects**: Combining different biostimulants can lead to additive or synergistic benefits due to complementary modes of action. For example, AMF and seaweed extract together showed synergistic effects on flowering and AMF root colonization in tomatoes.

Challenges, Opportunities and the Future

Despite their potential, widespread adoption of biostimulants faces several barriers, including inconsistent product performance due to complex interactions with crops, soil and climate, leading to skepticism. Regulatory uncertainty, a knowledge gap among growers and the presence of low-quality or untested products in the market also hinder adoption, undermining the industry's credibility and effectiveness.

However, the biostimulant sector is growing rapidly, driven by the expanding organic food sector, consumer demand for sustainable vegetables and the need for climate change adaptation. Regulatory landscapes are evolving, with the EU establishing specific categories and the USDA and EPA developing clearer guidance.

Future research and innovation are crucial for advancing biostimulant technology. Key areas include elucidating precise molecular and biochemical mechanisms using omics technologies, integrating biostimulants with precision agriculture tools like IoT sensors and AI, and developing advanced formulation technologies such as microencapsulation and nanotechnology to enhance stability, efficacy, and ease of use.

Conclusion

Plant biostimulants represent a pivotal advancement for sustainable vegetable production, enhancing crop quality, stress tolerance and post-harvest longevity while reducing reliance on synthetic inputs. Despite this potential, challenges like variable efficacy, regulatory uncertainty and the need for grower education impede their widespread adoption.

However, the sector is experiencing robust growth and a maturing regulatory landscape. Future success hinges on continued research into their molecular mechanisms, integration with precision agriculture and advanced formulation technologies. Ultimately, biostimulants are critical for developing a more circular and climate-resilient agricultural system, connecting waste valorization, climate adaptation and soil health.

References

1. Bulgari, R., Cocetta, G., Trivellini, A., Vernieri, P. A. O. L. O., & Ferrante, A. (2015). Biostimulants and crop responses: a review. *Biological Agriculture & Horticulture*, *31*(1), 1-17.
2. Corsi, S., Ruggeri, G., Zamboni, A., Bhakti, P., Espen, L., Ferrante, A., ... & Scarafoni, A. (2022). A bibliometric analysis of the scientific literature on biostimulants. *Agronomy*, *12*(6), 1257.
3. Drobek, M., Frąc, M., & Cybulska, J. (2019). Plant biostimulants: Importance of the quality and yield of horticultural crops and the improvement of plant tolerance to abiotic stress—A review. *Agronomy*, *9*(6), 335.
4. Gruda, N. S., Li, X., Gallegos-Cedillo, V. M., Samouline, G., Dong, J., Weiss, J., & Fernández, J. A. (2025). From growth to table: exploring the impact of pre-harvest conditions on greenhouse vegetable quality. *European Jo*
5. Li, J., Van Gerrewey, T., & Geelen, D. (2022). A meta-analysis of biostimulant yield effectiveness in field trials. *Frontiers in Plant Science*, *13*, 836702.
6. Miron, L. D. 2015. International Scientific Congress.
7. Pereira, R. V., Filgueiras, C. C., Dória, J., Peñaflor, M. F. G., & Willett, D. S. (2021). The effects of biostimulants on induced plant defense. *Frontiers in Agronomy*, *3*, 630596.
8. Ricci, M., Tilbury, L., Daridon, B., & Sukalac, K. (2019). General principles to justify plant biostimulant claims. *Frontiers in plant science*, *10*, 494.
9. Zhao, X., Peng, J., Zhang, L., Yang, X., Qiu, Y., Cai, C., ... & Wang, Z. (2024). Optimizing the quality of horticultural crop: insights into pre-harvest practices in controlled environment agriculture. *Frontiers in Plant Science*, *15*, 1427471.