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EDITORIAL

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Biostimulants in Agriculture: Editorial

Biostimulants are becoming an important tool in agriculture, helping to improve crop growth, resilience, and quality while supporting sustainable farming practices. These products, made from natural substances or microorganisms, enhance plants' natural processes. They can improve how plants use nutrients, handle stressful conditions like drought or salinity, and boost overall crop productivity and quality. The European Regulation (EU) 2019/1009 defines biostimulants as products "the function of which is to stimulate plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: (a) nutrient use efficiency; (b) tolerance to abiotic stress; (c) quality traits; or (d) availability of confined nutrients in the soil or rhizosphere". This regulation has helped clarify what biostimulants are while encouraging their disciplined use in agriculture (EU 2019). Although biostimulants have shown great potential, there is still much to learn about how they work and how to maximise their benefits. Their effectiveness depends on crop type, dose, and timing, with a particular focus on crop responses under suboptimal conditions. Biostimulants have great potential to address cropping challenges such as climate change, resource scarcity, and the need for more sustainable farming methods. They offer a practical approach to increasing food production despite abiotic constraints.

This Special Issue of Physiologia Plantarum "*Biostimulants in Agriculture*" includes seventeen studies that explore how biostimulants can help solve some of agriculture's biggest challenges. These studies investigate how biostimulants improve nutrient use efficiency, enhance plant stress tolerance, boost growth and increase quality traits. They also explore new formulations, like nanoparticles, and innovative concepts, such as glycostimulation, which uses various glycomolecules to enhance plant growth.

The research investigates the modes of action of biostimulants and their applications in real-world farming. Using advanced techniques, such as molecular studies and field experiments, these studies demonstrate how biostimulants can be tailored to different plant species, such as tomato, lettuce, maize, oilseed rape, cucumber, wheat, Indian mustard, Arabidopsis and grapevine, and growth conditions. Biostimulants are no longer just an experimental idea; they are becoming an essential part of sustainable agriculture.

The studies gathered in this issue provide valuable insights into how biostimulants can shape the future of farming, making it more productive, resilient, and eco-friendly. They also show how new findings can be directly transferred to the field, helping farmers use biostimulants effectively to improve the growth and quality of their produce.

1 | BIOSTIMULANTS ENHANCE NUTRIENT USE EFFICIENCY AND BIOMASS ACCUMULATION

Improving nutrient use efficiency (NUE) is a pivotal objective in sustainable agriculture, especially as the global demand for environmentally sound food production intensifies. Several studies in this issue highlight innovative approaches to enhancing NUE and promoting biomass accumulation. Monterisi et al. (2024) employed a multi-omics approach to investigate the role of protein hydrolysates (PHs) in nitrogen-limited lettuce plants. Their findings showed that PHs, particularly the low-molecular-weight fractions, act through hormone-like mechanisms to enhance nitrogen utilization, even under suboptimal nitrogen availability. These effects were linked to the upregulation of auxin and cytokinin biosynthesis pathways, the activation of multifaceted antioxidant responses, and enhanced cell wall plasticity, which collectively boosted plant growth and biomass accumulation under low nitrogen conditions.

Pathak et al. (2024) demonstrated the synergistic potential of combining microbial and non-microbial biostimulants in wheat. They developed bioinoculants that significantly improved germination, root architecture, and nutrient content by integrating a functionally competent synthetic microbial community with humic acid or seaweed extracts. Their field trials revealed that wheat plants treated with these integrated biostimulants achieved a 40% increase in grain yield and a substantial increase in macro- and micronutrient profiles. This study underscores the importance of blending microbial diversity with biostimulants to combine agricultural productivity and sustainability. Velasco-Clares et al. (2024) investigated the application of a seaweed-derived biostimulant enriched with bioactive anti-stress compounds under optimal growth conditions. Lettuce plants treated with the biostimulant at an optimal dose of 300 mL/hL showed improved biomass production, enhanced photosynthetic activity, and enriched phytohormones, amino acids, and mineral nutrient profiles. The treatment also stimulated nitrogen assimilation, antioxidant capacity, and concentrations of key antioxidant compounds, contributing to higher crop quality and potential stress resilience. However, the study highlighted the risk of phytotoxic effects at higher doses, such as 500 mL/hL, emphasizing the critical importance of proper dosage for maximizing the benefits of biostimulants.

2 | BIOSTIMULANTS REGULATE GROWTH, DEVELOPMENT, AND QUALITY TRAITS

Biostimulants may promote plant growth and development by influencing key physiological and molecular pathways. In *Arabidopsis thaliana*, Bahmani and Prithiviraj (2024) demonstrated that extracts from *Ascophyllum nodosum* regulate flowering time through the "MIR156-mediated age pathway", a central mechanism in developmental transitions. These extracts modulate the balance between key flowering regulators by repressing MIR156, a negative regulator, and enhancing SPLs and MIR172, which promote flowering while downregulating floral repressors like AP2-like genes. Using fucoidan, a compound derived from the seaweed extract, they further highlighted the ability of extract compounds to mimic sugar signalling and activate the flowering pathway. Similarly, Ancín et al. (2024) explored the effects of microalgal and PH extracts on oilseed rape (*Brassica napus*) and observed significant enhancements in phenological transitions and yield. These improvements were linked to better photosynthetic performance and accelerated developmental processes supported by changes in proteomic and metabolomic profiles. The biostimulants also upregulated antioxidant enzymes, helping plants manage the stress due to rapid phenological changes. Mutlu-Durak et al. (2024) demonstrated that extracts from the brown seaweed *Cystoseira barbata* significantly enhanced root and shoot growth in wheat (*Triticum durum*) seedlings. Among the various extraction methods tested, water-based extracts applied to the substrate proved to be the most effective. These treatments increased biomass accumulation and positively affected root morphology and nutrient uptake, highlighting the critical role of biostimulants in optimizing early-stage plant growth. The authors point out that additional studies are required to explore the effects of soil and foliar applications of these extracts on growth, yield, and stress tolerance. Furthermore, the potential of these extracts in soilless systems, as well as the efficacy of 'greener' *C. barbata* extracts like supercritical and cold-pressed variants, must be assessed.

In a study on a table grapevine variety, Peli et al. (2025) reported that the soil application of maize gluten-derived protein hydrolysate (GDPH) led to a shift in berry development dynamics, improving quality characteristics such as increased anthocyanin and sugar levels, larger berry diameter, and preserved berry firmness. Interestingly, the transcriptomic analysis revealed that GDPH influenced the expression of genes involved in accelerating ripening-specific metabolic processes, including the repression of green/immature berry development and cell-wall softening pathways while promoting genes involved in anthocyanin synthesis.

3 | BIOSTIMULANTS BOOST TOLERANCE TO ABIOTIC STRESSES IN CROPS

Abiotic stresses such as drought, salinity, extreme temperatures, and heavy metal toxicity are critical challenges in agriculture, substantially reducing crop productivity and posing a threat to global food security. Biostimulants are emerging as innovative solutions to alleviate these effects by enhancing plant resilience through various biochemical and physiological mechanisms. Cerruti et al. (2024) investigated the effects of an algae-based (*A. nodosum* and *Laminaria digitata*) biostimulant on tomato plants subjected to mild drought stress, revealing its ability to prime plants by modulating early stress markers and regulating reactive oxygen species (ROS) levels through enzymatic and non-enzymatic scavengers. This priming induced endogenous defence mechanisms before plants were exposed to stress, thus preventing oxidative damage and protecting plant physiological functions. Transcriptomic analysis further highlighted its role in modulating genes linked to water transport, oxidative stress response, and cellular organization. The authors suggest that the selected timings and the adopted RNA-seq data analysis techniques, by either monitoring differentially expressed genes or groups of coregulated genes, can be a valid, future approach to provide further information about biostimulant mode of action. Similarly, Brown et al. (2024) demonstrated that chitosan-fulvic acid nanoparticles (Ch-FANPs) enhance drought tolerance in maize by activating antioxidant enzyme activities, including ascorbate peroxidase (APX) and catalase (CAT), and reducing lipid peroxidation and hydrogen peroxide (H_2O_2) accumulation. This treatment also induced the expression of key drought-responsive transcription factors involved in signaling pathways and water-use efficiency, offering a comprehensive mechanism for improved resilience under water deficit conditions. Salinity stress, which disrupts ionic balance and water uptake, was addressed by Islam et al. (2024) through the application of glycine betaine (GB) in Indian mustard (*Brassica juncea*). GB improved osmotic regulation and cellular ionic homeostasis, reduced oxidative damage, and increased growth, biomass, and nutrient uptake even under high salt concentrations. Meanwhile, heavy metal toxicity due to cadmium (Cd) was mitigated in grapevine seedlings using smoke solutions (SS) derived from vineyard pruning waste, as reported by Yağcı et al. (2024). The application of 0.5% SS enhanced antioxidant defences by upregulating the activity of enzymes such as superoxide dismutase (SOD), CAT, and APX, reducing malondialdehyde (MDA, marker of lipid peroxidation) levels, and preserving photosynthetic efficiency and membrane integrity. The study showed that transforming organic plant waste into smoke solutions provides an eco-friendly approach to boosting the sustainability of viticulture and adding value to waste materials. However, future studies are needed to investigate the interactions between smoke solutions and heavy metals and their effects on grapevine yield. A study by Daler and Kaya (2024) explored the use of alpha-lipoic acid as a foliar treatment to reduce oxidative damage in two grapevine rootstocks with different levels of drought tolerance: the drought-tolerant '1103 P' and the drought-sensitive '3309 C'. Treatments with alpha-lipoic acid significantly improved physiological parameters, such as chlorophyll content, stomatal conductance, and antioxidant enzyme activities (SOD, CAT, APX), while decreasing electrolyte leakage and MDA levels under drought conditions. Particularly, the rootstock '1103 P' demonstrated superior performance at a concentration of 50 μM alpha-lipoic acid, emphasizing the importance of rootstock selection in optimizing responses to drought stress. These findings highlight the potential of alpha-lipoic acid as a natural and eco-friendly biostimulant for improving grapevine resilience in water-limited environments. The arbuscular mycorrhizal fungi *Rhizophagus irregularis* and biochar (BC) were shown by Wen et al. (2024) to synergistically improve the growth and physiological characteristics of switchgrass under saline-alkali stress. Their combined application significantly increased plant biomass, photosynthetic efficiency, and antioxidant enzyme activity compared to individual treatments. The combined treatment also enhanced light response parameters, stomatal conductance, and the maximum electron transfer rate, offering a promising strategy to mitigate saline-alkali stress and improve crop productivity. A study on *Bacillus zanthoxyli* HS1 (BzaHS1) by Barghi and Jung (2024) demonstrated its effectiveness in mitigating salt and heat stress in cabbage and cucumber plants. Application of BzaHS1 or its volatile organic compounds (VOC) enhanced seedling growth under stress conditions by reducing oxidative stress through increased enzymatic activities of SOD, CAT and APX. Additionally, BzaHS1 triggered callose accumulation and minimized stomatal opening, further enhancing plant resilience. These findings highlight the potential of BzaHS1 and its VOC in improving systemic plant tolerance to abiotic stresses through modulation of stress-regulatory networks. Low-temperature stress, another significant abiotic challenge, was addressed by Sun et al. (2024), who demonstrated that the combined myo-inositol and corn steep liquor enhanced seedling growth and cold tolerance in cucumber and tomato. This treatment improved photosynthetic pigment levels, reduced MDA and electrolyte leakage, and upregulated cold-responsive genes, such as *CBF1* and *COR*. Notably, the synergistic effects of myo-inositol and corn steep liquor provided significant protection under low-temperature stress, promoting early crop growth and resilience. Jasso-Robles et al. (2024) explored the role of putrescine, a small molecule, as a biostimulant in *Arabidopsis*. Their research showed that putrescine enhances plant growth and photosynthesis by influencing critical genetic and metabolic pathways. Putrescine application was particularly effective under stress conditions, such as high salinity, where it helps plants maintain their performance. This study highlights putrescine as a promising tool for improving crop tolerance and growth. Finally, in a comprehensive review article, Boulogne et al. (2024) introduced the concept of "glycostimulation", identifying glycomolecules such as polysaccharides, glycoproteins, and glycolipids as a distinct and versatile category of biostimulants. These compounds may play the dual role of enhancing plant response mechanisms against both abiotic and biotic stresses while simultaneously promoting growth. This unique combination of benefits positions glycomolecules as a promising focus for advancing agricultural productivity and plant health, offering a bridge between stress resilience and improved yield potential.

4 | CONCLUSION

Biostimulants are transforming modern agriculture by providing diverse and innovative strategies to enhance nutrient acquisition, biomass production, stress tolerance, and overall crop performance. The studies assembled in this Special Issue demonstrate how biostimulants regulate plant growth, development, and quality traits of different crop species at various developmental stages, from early vegetative stages to reproductive transitions, showcasing their ability to improve productivity and sustainability. Biostimulants have shown their multifaceted role in addressing key agricultural challenges through molecular modulation, microbial integration, and the application of seaweed-derived products. Advanced formulations and novel mechanisms, such as glycostimulation and nanoparticle-based products, are redefining how we manage crops, offering new perspectives for sustainable farming. These findings underscore the growing importance of biostimulants in real-world agricultural applications, especially in overcoming challenges posed by climate change and resource limitations. By bridging scientific discovery with practical implementation, biostimulants provide valuable tools to create resilient, productive, and environmentally friendly farming systems, making them an important part of the future of agriculture. Collectively, these studies demonstrate the ability of biostimulants to challenge various abiotic stresses through mechanisms that include improved antioxidant activity, ionic balance, osmotic regulation, and transcriptional reprogramming, underscoring their potential as a sustainable tool for enhancing crop resilience in challenging environmental conditions while preserving or promoting growth and quality.

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