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Seaweed Derived Biostimulants for Super crops: Revolutionizing Sustainable Agriculture

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Marine plants, especially seaweeds are increasingly recognized as valuable natural resources for developing sustainable biostimulants in modern agriculture. This review discusses the growing role of marine-derived biostimulants in improving crop productivity while reducing the dependence on synthetic fertilizers and chemical inputs. Marine plants contain diverse bioactive compounds, including polysaccharides, phytohormones, amino acids, vitamins, minerals, and antioxidants, which enhance plant growth, nutrient absorption, beneficial microbial activity, and tolerance to environmental stresses such as drought, salinity, and temperature fluctuations. Recent progress in extraction methods, commercial applications, quality control, and regulatory challenges is also explored. Furthermore, future research opportunities involving biotechnology and omics-based approaches are highlighted. Overall, marine-derived biostimulants represent a promising eco-friendly approach for sustainable agriculture and improved global food security.

Keywords: Marine plants; Biostimulants; Seaweed extracts; Sustainable agriculture; Crop productivity.

Introduction

By 2050, global food demand is projected to increase by 70–100%, placing considerable pressure on agricultural systems to enhance productivity while reducing environmental impacts (Gomiero et al., 2011). Although intensive farming has significantly improved crop production, it has also contributed to biodiversity decline, soil degradation, ecosystem imbalance, water pollution, and increased greenhouse gas emissions. These concerns emphasize the importance of developing sustainable agri-food systems that balance productivity, environmental conservation, and economic sustainability (Dönmez et al., 2024). Approaches such as precision agriculture, biotechnology, agroecological practices, and climate-smart farming provide opportunities to improve crop yields while maintaining essential ecosystem services. Practices including crop diversification, intercropping, improved nutrient management, biological nitrogen fixation, and natural pest regulation can further strengthen agricultural resilience and support long-term food security (Cakmakci et al., 2025). Plant biostimulants have gained increasing attention as sustainable inputs that improve plant growth, nutrient efficiency, and tolerance to environmental stresses while reducing reliance on chemical fertilizers (Chiaiese et al., 2018). Among these, marine-derived biostimulants, particularly those obtained from macroalgae, are rich in bioactive compounds such as polysaccharides, phytohormones, amino acids, antioxidants, and minerals. These compounds promote plant growth, enhance photosynthetic activity, improve nutrient uptake, and increase tolerance to drought and salinity (Staykov et al., 2025). Despite their growing application, further research is needed to clarify their molecular mechanisms and improve product consistency. Recent advances in metabolomics, transcriptomics, and phenomics are helping to understand their role in plant development and stress responses, while improved extraction methods and regulatory frameworks are essential for their wider sustainable use (Magnabosco et al., 2023).

Overview of Marine Plants in Agriculture: Seaweeds

Marine-derived biostimulants have emerged as sustainable agricultural tools due to their ability to improve plant growth, nutrient-use efficiency, and stress tolerance. Macroalgae and microalgae contain bioactive compounds such as phytohormones, polysaccharides, minerals, amino acids, vitamins, and phenolic compounds that enhance root development, photosynthesis, nutrient uptake, and resistance to drought, salinity, and temperature stress (Sekar et al., 2025;). These compounds also stimulate defense-related genes and antioxidant enzymes, improving plant resilience and soil health (Ali et al., 2021). However, challenges related to sustainable harvesting, extraction methods, product standardization, and regulatory frameworks remain (Rabhi et al., 2025). Further research using metabolomics and molecular approaches is needed to optimize their agricultural applications (Calvo et al., 2014).

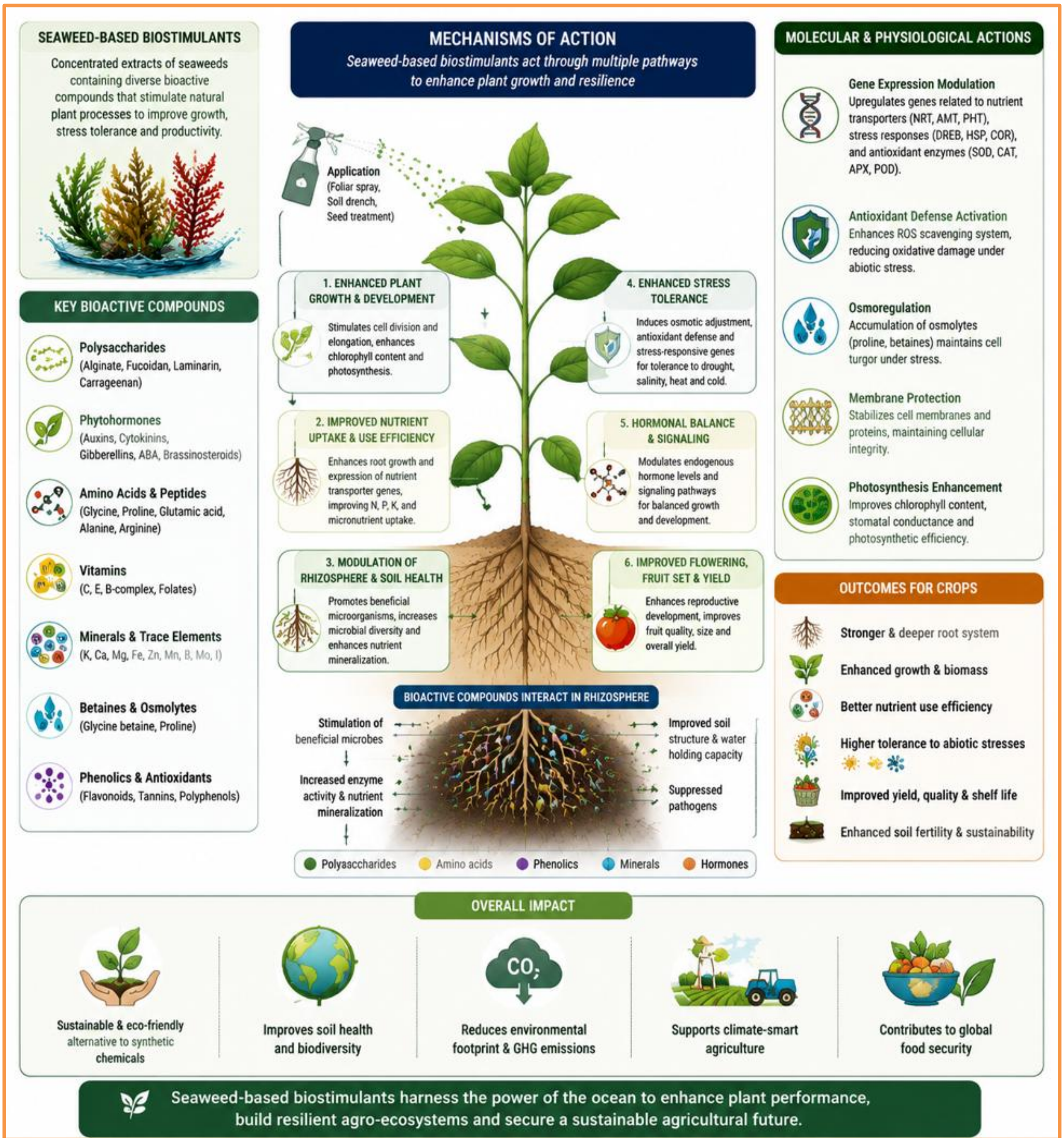

Fig.1 Mechanisms of action of seaweed-based biostimulants in plants

Nutrient and Bioactive Composition of Seaweed-Based Biostimulants

Marine-derived biostimulants contain diverse bioactive compounds, including polysaccharides, phytohormones, amino acids, betaines, polyamines, minerals, and secondary metabolites, which regulate plant metabolism and improve tolerance to abiotic stresses (Abarnadevi et al., 2025). These compounds enhance nutrient transport, proline accumulation, antioxidant activity, and reduce oxidative damage caused by drought, salinity, and temperature stress (Asif et al., 2023). Seaweed polysaccharides such as laminarins, ulvans, and carrageenans also act as phytoelicitors by activating plant defense responses against pathogens (Fig.1). Recent advances in omics technologies have improved understanding of the molecular mechanisms of seaweed biostimulants. They regulate stress-responsive genes, maintain photosynthesis, improve antioxidant defense, and enhance plant resilience under environmental stress conditions (Senthilkumar et al., 2019). Additionally, these compounds promote beneficial soil microbes, improve nutrient uptake, and strengthen soil–plant interactions. Whole seaweed extracts often show greater effectiveness than individual compounds, with reported yield improvements of 16–18% (Arioli et al., 2023).

Mechanisms of Seaweed as Biostimulants and Biofertilizers

In particular, seaweed extract-derived biostimulants have a synergistic effect on plant growth and stress resistance by influencing various physiological and metabolic mechanisms involving phytohormones, polysaccharides, amino acids, betaines and other bioactive compounds. The enhancement of root architecture, nutrient uptake, photosynthetic efficiency, osmotic adjustment, and antioxidant activity are important for plants to survive drought stress, salinity stress, and temperature stress, respectively. They also encourage beneficial microbes of the rhizosphere and enhance the expression of genes of nutrient transporters that are responsible for the assimilation of nitrogen, phosphorus, and sulfur under stressful conditions (Raj et al., 2022). Recent molecular studies revealed that extracts from seaweeds regulate stress responsive genes, maintain ion homeostasis, increase aquaporin expression and activate antioxidant pathways, which enhance plant resistance and productivity under environmental stress (Elumalai et al., 2025). Still, the variability of algal species, extraction processes, and product formulations requires standardized production and advanced omics research to discover key bioactive molecules and optimize field performance, however (López-Serrano et al., 2026).

Marine Biostimulants vs. Traditional Fertilizers

The use of seaweed-based biostimulants is gaining traction as an eco-friendly option to chemical fertilizers, as they can enhance soil structure, boost nutrient uptake efficiency, and help plants cope with abiotic stresses while having less environmental footprint than conventional farming systems (Rafi et al., 2025). The marine bio-extracts are rich in polysaccharides, phytohormones, and bioactive compounds, which boost the plant's defense mechanisms, enhance root development, optimize water and nutrient uptake, and bolster the resilience against drought, salinity, and temperature extremes. They are also adopted as part of a circular bioeconomy, because the use of synthetic agrochemicals and petroleumbased inputs is reduced. However, obstacles such as availability of biomass, product standardization and quality control and regulatory harmonization still exist for largescale commercialization (Baltrusch et al., 2023). Future study with the incorporation of omics technologies and standardizing the application protocols will be fundamental for enhancing formulation and increasing the agricultural potential of seaweed biostimulants in different cropping systems (Abdelkader et al., 2025).

Environmental benefits: reducing chemical fertilizers and pesticides

Soil health has been affected by overuse of synthetic fertilizers and pesticides, contributing to nutrient leaching and eutrophication which in turn causes water pollution; this is due to the loss of microbial diversity (Nivetha et al., 2024). These benefits make seaweed-derived biostimulants a sustainable alternative that can help farmers reduce their reliance on synthetic agrochemicals and boost soil health and nutrient efficiency. The extracts are rich in phytohormones, polysaccharides and other bioactive compounds, which enhance nutrient uptake, drought, salinity and heat stress tolerance, soil structure and fertility. They also play a role in promoting a circular bioeconomy by reducing greenhouse gas emissions, the need for fertilizer, enhancing carbon sequestration, and minimizing environmental pollution, while ensuring sustainable agriculture in the long run (Hilles et al., 2025).

Economic implications for farmers and the agricultural industry

The shift towards a bio-based agricultural economy has sparked interest in the use of seaweed based biostimulants as alternative to petroleumbased agrochemicals. In addition to lessening environmental impacts, these products help boost crop productivity, reduce fertilizer use by up to 25%, and yield almost 18% more, which has a positive impact on farm profitability and overall economy (Skapste et al., 2025). In addition, seaweed biostimulants help mitigate loss of yield due to drought, salinity and other abiotic stresses, resulting in higher economic profits for farmers. For greater commercialization, long-term field trials, profitability studies, and life-cycle assessments must be performed to assess their economic and environmental impact across different farming systems. The use of improved extraction techniques, standardization, and economies of scale should lower the production costs and increase market competitiveness (Choulot et al., 2025). In addition, the possibility of using automated harvesting, biorefinery processes, and valorization of algal by-products can help improve the commercial viability of sustainable agriculture-based industry and create new value chains (Pacheco et al., 2024).

Challenges and Opportunities in the Marine Biostimulant Market

Marine biotechnology is a huge game-changer for the development of sustainable seaweed based biostimulants and the technical, regulatory, and commercial hurdles are yet to be overcome (Berthon et al., 2021). Marine extracts are complex, and the raw materials are variable, so it is challenging to pinpoint the exact mode of action; current regulations focus more on the source of products than on their biological activities (Yakhin et al., 2017). Product authenticity, reduced content of heavy metals and quality standardization are key to safe commercialization. Advanced omics technologies, high throughput phenotyping and better extraction techniques are helping to deepen understanding of bioactive compounds, and to develop standardized, quality formulations. However, future advancements will rely on harmonization of regulations, bioassay-guided validation, large-scale field trials, optimized extraction technologies and synergistic formulations, integrating seaweed extracts with microbial inoculants to ensure consistent performance across a broad range of agroecosystems (Quille et al., 2024).

Sustainability and the Future of Marine Biostimulants

Seaweed and microalgal resources are important renewable ingredients in marine biotechnology for sustainable agriculture (Rotter et al., 2020). Seaweed-based biostimulants can lead to reduced reliance on synthetic fertilizers and pesticides, enhance crop resilience, promotesmart climate agriculture, and help mitigate nutrient loss and environmental pollution (Parmar et al., 2023). For large scale use, product standardization, monitoring of contaminants and optimization of extraction technologies should be improved to guarantee quality and effectiveness. Future advances will rely on integrating omics technologies, advanced phenotyping and implementing standardized efficacy markers to gain a deeper understanding of molecular mechanisms and validation of field performance in different crops and environments (Saeger et al., 2019).

Conclusion

Marine plants are a potentially important and sustainable source for the formulation of future generation biostimulants, which can be used in a way that will be beneficial to resilient and environmentally responsible agriculture. The marine plant extracts containing bio active compounds such as polysaccharides, phytohormones, amino acids, vitamins, and minerals can stimulate plant growth, nutrient assimilation, stress resistance, and yield, while cutting down on the use of synthetic agrochemicals. They have diverse modes of action and help to boost soil health, microbial activity and resilience to abiotic stress conditions including drought, salinity, and temperature fluctuations. Despite the above benefits, problems of standardization, mass production, regulatory harmonization and the understanding of their molecular mechanisms exist. Advanced extraction technologies, omics-based approaches and field validations to optimize the effectiveness of these in various cropping systems are recommended for future research. In conclusion, marine plants hold immense promise for revolutionizing sustainable agriculture, offering environmentally friendly biostimulant solutions that can enhance food security, environmental protection, and sustainable crop production.

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