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Evaluation of biostimulants from nature-based substances: Promoting crop resilience and land sustainability models

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INTRODUCTION & AIM

- Climate change and ecosystem degradation **threaten food security.**
- Agriculture contributes **~23% of net anthropogenic GHG emissions (IPCC).**
- Intensive synthetic fertilizers/pesticides and poor soil practices drive emissions.
- **Bio-based formulations (biostimulants)** support healthy crop growth and pest resilience.
- Biostimulants **improve nutrient uptake, stress tolerance, and soil microbiota health.**
- They promote **agroecosystem sustainability** and facilitate organic certification.
- EU and EBIC require **scientific evidence** for biostimulant efficacy and mechanisms.

The aim of this review is to assess how natural biostimulants help improve crop resilience and soil health for sustainable agriculture. It focuses on evaluating their effectiveness, how they work, and their role in supporting sustainable land management.

EFFICACY OF BIOSTIMULANTS

Craigie et al. (2011) and **Goñi et al. (2018),** report that ***Ascophyllum nodosum* extracts (2–4 L/ha)** increase wheat yield by 8–15% under drought by improving antioxidant activity. **Rathore et al. (2009),** showed **that *Moringa oleifera* leaf extracts (3% foliar spray)** raise maize biomass by 12–18% and chlorophyll content by ~20% under salinity.

Meta-analyses by Rouphael and **Colla (2020)** and **du Jardin (2015),** indicate that natural biostimulants enhance nutrient use efficiency by 10–25% and water productivity by 10–20%, supporting sustainable intensification under abiotic stress.

MECHANISM OF ACTION

Biostimulants act through molecular and physiological pathways to improve stress resilience **(Figure 1).** For example, ***A. nodosum*** delivers betaines and cytokinins that enhance osmoprotectant synthesis and ROS scavenging. Meanwhile, ***M. oleifera*** provides cytokinins (zeatin) and polyphenolic antioxidants that boost cell division, chlorophyll content, and antioxidant enzyme activity (SOD, CAT).

Biostimulants also **remodel root architecture, increasing lateral roots** and **root hairs for better water** and **nutrient uptake under stress.**

This supports improved photosynthetic **efficiency and biomass accumulation under abiotic stress.** Field results confirm these mechanisms translate into enhanced yield stability.

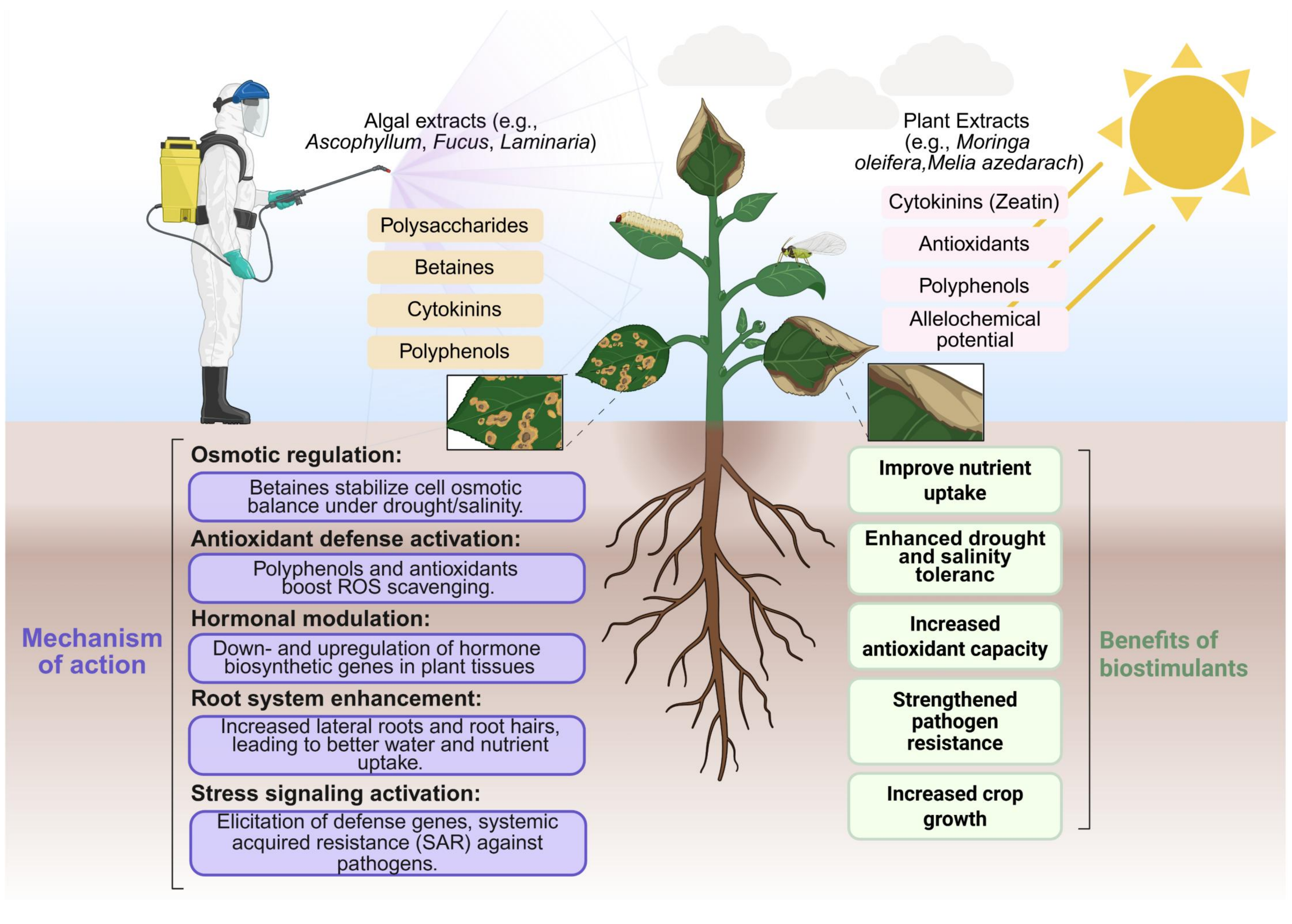

Figure 1. Seaweed extracts and botanicals: mechanisms and effects as biostimulants.

IMPACT ON PLANT RESISTANCE

Biostimulants enhance **plant resilience to biotic and abiotic stresses (Figure 2)** by modulating immune signaling pathways and fortifying cellular defense mechanisms.

Specifically, **algal-derived polysaccharides (e.g. fucoidans)** function as **microbe-associated molecular pattern mimics**, triggering **pattern-triggered immunity** in plants. This leads to the upregulation of **defense-related transcription factors (e.g., WRKY, ERF families), mitogen-activated protein kinase (MAPK) cascades**, and the biosynthesis of **pathogenesis-related (PR) proteins** and **phytoalexins** with antimicrobial activity.

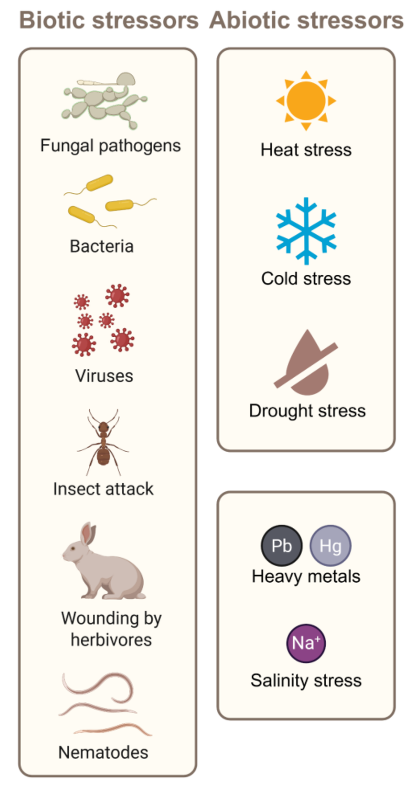

Figure 2. Stressors

Concurrently, **phytochemical constituents (e.g., zeatin, flavonoids, and phenolic acids)** enhance **enzymatic antioxidant defense systems**, including **SOD, CAT, and ascorbate peroxidase (APX)**, reducing ROS accumulation under **salinity, drought, and heat stress.** Furthermore, these compounds modulate **abscisic acid (ABA) and salicylic acid (SA) signaling**, improving **stomatal regulation and osmotic adjustment** under water-deficit conditions. This **dual stressors mitigation** reduces crop vulnerability, maintains **photosynthetic efficiency**, and supports **yield stability under suboptimal conditions**, facilitating a reduction in synthetic agrochemical inputs while maintaining plant productivity.

MODELS FOR CROP RESILIENCE AND SUSTAINABILITY

Table 1. Modeling biostimulant contributions to agroecosystem resilience.

ASPECT	EMPIRICAL MODELS	CONCEPTUAL MODELS
Approach	Multivariate statistical analysis (PCA, PLSR)	Soil-plant-atmosphere frameworks
Evaluated variables	Physiological markers (e.g., chlorophyll fluorescence)	Microbial diversity, nutrient cycling, carbon dynamics
Quantified outcomes	NUE, WUE, STI under stress	N mineralization, P solubilization, C dynamics
Contribution to system	Field evidence of efficacy	Supports regenerative systems and ecosystem services

PCA (Principal Component Analysis); PLSR (Partial Least Squares Regression); NUE (Nitrogen Use Efficiency); WUE (Water Use Efficiency); STI (Stress Tolerance Index); N (Nitrogen); P (Phosphorus); C (Carbon).

MATHEMATICAL AND SIMULATION MODELS

Process-based mathematical models elucidate the dynamic interactions between biostimulants, plant physiological processes, and environmental drivers. These models incorporate:

- **Mechanistic representations of hormonal modulation** (e.g., cytokinin/auxin ratios, ABA signaling),
- **Stress signaling pathways** (MAPK cascades, ROS signaling),
- **Nutrient uptake kinetics** (Michaelis-Menten dynamics for nitrate and phosphate transporters).

Simulation platforms (e.g., APSIM, DSSAT) allow scenario analysis for **application timing, dose-response curves, and cumulative impacts on soil health and GHG emissions** under different climate scenarios.

Integration of **remote sensing data (NDVI, thermal indices) and proximal sensing (soil moisture, electrical conductivity)** with **machine learning algorithms** enhances predictive capabilities for biostimulant efficacy, enabling **precision agriculture implementation** with site-specific recommendations.

CONCLUSION

Biostimulants improve **crop resilience by activating plant defense** and **stress tolerance** mechanisms while enhancing soil health and **reducing dependence on synthetic inputs.** To fully realize their potential, biostimulant use requires **locally adapted strategies,** continuous **monitoring** of efficacy, and consideration of **long-term ecosystem impacts.** Integration at farm and landscape levels, aligned with **stakeholder collaboration** and **regulatory frameworks,** is essential for transitioning towards profitable, climate-resilient, and sustainable agriculture.

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