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SEAWEED BIOSTIMULANTS IN SUSTAINABLE AGRICULTURE: A SCIENTOMETRIC-SYSTEMATIC REVIEW OF MECHANISMS, EFFICACY, AND KNOWLEDGE GAPS

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SUMMARY

The following study aimed to conduct an integrative scientometric and systematic review of seaweed-derived biostimulants and their vital role in sustainable agriculture, analyzing numerous publications (2000–2025) and the findings of 25 experimental studies. The Scopus, ScienceDirect, and Web of Science databases, keyword co-occurrence, thematic, and factorial analyses were approaches used to explore the global research trends, the important species, and agronomic impacts. *Ascophyllum nodosum*, *Ecklonia maxima*, and *Gracilaria* emerged as dominant species with consistent positive effects on crop performance, including crop growth and development, nutrient uptake, chlorophyll content, stress tolerance, and antioxidant activities. Leading journals and institutions, particularly those in China and India, drive innovation in this field. Field studies also confirmed dose-dependent efficacy, with foliar applications (0.1%–0.5%) and soil drenches (0.5–2 g/L) improving crop yields under abiotic stress conditions. Despite these benefits, gaps remain in extract standardization, molecular mechanisms, and large-scale application. This study underscores the need for interdisciplinary approaches to translate marine biostimulant research into scalable and climate-resilient agricultural practices.

Keywords: Biostimulant, productivity, review analysis, seaweed, sustainable agriculture

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Key findings: This review highlighted the *Ascophyllum nodosum* (brown alga) as the most studied seaweed species for boosting plant growth and development and stress tolerance through foliar and soil applications, despite challenges in standardization and scalability.

INTRODUCTION

With the present climate change, the urgency for sustainable agricultural intensification has increased the global demand for eco-friendly inputs. Conventional methods relying heavily on synthetic fertilizers and pesticides, although effective in the short term, have resulted in soil degradation, water pollution, and reduced biodiversity, creating long-term sustainability challenges for modern agriculture. In this context, seaweed-derived biostimulants have gained attention as promising alternatives, not only to enhance crop productivity but also to improve abiotic stress resilience while reducing dependence on synthetic agrochemicals (Battacharyya *et al.*, 2015; Shukla *et al.*, 2019). Seaweed extracts are particularly suited for addressing these agricultural challenges because they contain diverse bioactive compounds that function through multiple physiological and biochemical pathways. They have demonstrated wide-ranging positive effects on plant growth and development, including stimulation of germination, enhanced nutrient uptake, stress tolerance, and improved fruit quality (Ertani *et al.*, 2018; Ali *et al.*, 2019; Miceli *et al.*, 2021).

Empirical studies across major crops, vegetables, and fruits (tomatoes, lettuce, cereals, and citrus) have revealed that biostimulants function through multifactorial physiological and biochemical pathways. These are nutrient use efficiency (Alam *et al.*, 2013; Biswajit *et al.*, 2013), reactive oxygen species (ROS) scavenging (Rouphael *et al.*, 2018; Mattner *et al.*, 2023), modulation of rhizosphere microbiomes (Spann and Little, 2011; Alam *et al.*, 2014), and hormone-like activity linked to auxins, cytokinins, and betaines (Deolu-Ajayi *et al.*, 2022). For instance, field trials have also reported that *A. nodosum* extracts can enhance tomato yield under drought stress conditions (Ali *et al.*, 2019; Papoui and Koukounaras, 2025) and

improve strawberry fruit quality through multi-year trials (Alam *et al.*, 2013; Holden and Ross, 2017). Moreover, in hydroponics and saline soil applications, the seaweed species *E. maxima* and *Cystoseira* extracts have enhanced the lettuce biomass and wheat root development (Miceli *et al.*, 2021; Elbakkosh *et al.*, 2022; Mutlu-Durak *et al.*, 2024).

Despite the expanding empirical base, there remains a need for systematic and evidence-based information regarding research structure and dynamics underlying this field. Scientometrics approaches offer various tools to visualize the intellectual, thematic, and geographic evolution of biostimulants-related research and identification of influential studies, knowledge gaps, and future opportunities (Deolu-Ajayi *et al.*, 2022; Pei *et al.*, 2024). The bibliometric analysis of publications indexed in Scopus, ScienceDirect, and Web of Science (2000–2024) also revealed several dominant research clusters. Thematic mapping via keyword co-occurrence analysis highlighted both mature and emerging topics as well as notable gaps, such as the lack of standardized extraction protocols, variations in plant species responses, and limited life-cycle assessments for commercial biostimulant formulations (Comin *et al.*, 2024).

In addressing all these complexities, the presented study integrates scientometrics analysis with a systematic literature review to provide a comprehensive evaluation of seaweed extract's role in plant sciences. Specifically, this study aimed to map the thematic and structural evolution of seaweed biostimulants-related scientific research and synthesize empirical findings on agronomic and physiological effects of biostimulants across various crops, environments, and application methods. It also sought to identify the key knowledge gaps to synthesize the evidence-based applications and policy development in sustainable agriculture.

MATERIALS AND METHODS

Addressing all these complexities made the presented study integrate scientometric analysis with a systematic literature review to provide a comprehensive evaluation of seaweed extract's role in plant sciences. Specifically, the research aimed to map the thematic and structural evolution of seaweed biostimulants-related scientific research. It involved the synthesis of empirical findings on agronomic and physiological effects of biostimulants across various crops, environments, and application methods. Moreover, the study sought to identify the key knowledge gaps to synthesize the evidence-based applications and policy development in sustainable agriculture.

RESULTS AND DISCUSSION

Most relevant sources

Scientometric analysis revealed specialized journals that dominate research on seaweed's biostimulant effects on crop plants, with the Journal of Applied Phycology leading (94 articles) on marine biomass valorization for sustainable agriculture. Following it were Marine Drugs (77 articles) on bioactive compounds enhancing plant resilience and PLOS ONE (41 articles) validating agroecological benefits such as salinity tolerance. These journals' hierarchy aligns with Segaran *et al.*'s (2024) longitudinal analysis, which documented a 17-fold increase in seaweed publications from 1975–2021, reflecting a global shift toward marine bioresources as sustainable agricultural inputs. The journal Frontiers in Plant Science (27 articles) explores molecular mechanisms, such as photosynthetic efficiency, while Marine Pollution Bulletin (34 articles) highlighted the dual role of seaweed in pollutant adsorption and improvement in general soil health. The co-citation networks identified the Journals of Marine Biotechnology and Bacteriology as central hubs for environmental applications, demonstrating that these journals bridge marine chemistry and soil remediation, thereby

accelerating knowledge transfer within circular economy frameworks (Gazali *et al.*, 2024).

Despite contributions from the journals Agronomy (46 articles) and Horticulturae (21 articles), limited outputs in traditional journals suggest opportunities to integrate marine biostimulants into mainstream agronomy. Institutionally, the University of Karachi, Pakistan, leads with 74 publications on coastal agro-ecosystems, followed by Pukyong National University, South Korea, and King Saud University, Saudi Arabia. Asian countries dominate citation metrics, with India leading (6,202 citations) on seaweed extracts for crop yields and China (5,755 citations) on large-scale *Sargassum* application. South Korea and Japan showed the highest research impact despite fewer publications. However, regional disparities persist in Africa and Latin America, underscoring the need for cross-disciplinary collaboration, global knowledge-sharing, and targeted research to optimize the scalability of seaweed biostimulants and foster climate-resilient agricultural practices.

Trend topics

Trend analysis (2012–2024) using the 2000–2025 database highlighted the evolution of research on seaweed's biostimulant effects on crop plants. The term 'seaweed extract' (frequency: 837) dominates and reflects its key role in boosting plant growth and development (frequency: 423) as well as stress resilience. Segaran *et al.* (2024) identified 'extraction' as a top keyword with considerable citation bursts (2016–2022), signaling intensified efforts to optimize techniques for bioactive compound isolation across industries. Their analysis further correlates this burst with industrial demand for standardized, scalable biostimulants. Studies on the species *Ascophyllum nodosum* (frequency: 243) surged post-2015, revealing its extracts can significantly improve the antioxidant activity (frequency: 178) and amino acid synthesis (frequency: 139) under abiotic stress conditions. Concurrently, Gazali *et al.* (2024) contextualize shifting priorities; their burst analysis showed 'secondary metabolites' (strength: 2.21, 1996–2009) and

'marine macroalgae' (2.52, 2011–2016) dominated the earlier eras.

The growing prominence of 'drought stress' (frequency: 137; median year: 2023) and 'foliar application' (frequency: 150; median year: 2022) indicates a shift toward optimizing delivery methods in arid regions' agriculture. Bioactive compounds (frequency: 119) gained attention post-2019, linked with the examination of polysaccharides and phytohormones that enhance the growth rate (frequency: 119) in cereal and legume crops. However, alarming interest in 'brown seaweed' (frequency: 260; peak Quartile 3: 2022) compared with rising terms like 'drought stress' (Quartile 3: 2024) suggests a move from taxonomic exploration to applied stress physiology. Overall, the said trends enunciated the field's progression from basic marine biomass studies to targeted applications for climate resilience, though challenges remain in standardizing extraction protocols and scaling up field-ready solutions.

Keyword co-occurrence network

The keyword co-occurrence network analysis underscores the centrality of 'seaweed extract' and 'plant growth' as dominant themes, reflecting their pivotal role in research on the positive effects of seaweed biostimulants. Meena *et al.* (2025) identified seaweed extracts as the foremost biostimulant category, followed by humic substances and microbial agents. Their research confirms brown seaweed-derived biostimulants enhanced nutrient absorption and antioxidant-driven stress tolerance in cereals and horticultural crops, with drought mitigation being the primary focus (35% of abiotic stress studies). The considerable linkage between 'seaweed extract' and 'antioxidant activity' highlighted the mechanistic focus on how bioactive compounds in brown seaweeds (*Ascophyllum nodosum*) mitigate the oxidative stress, enhance cellular resilience, and promote growth in tomatoes and cereal crops. The frequent co-occurrence of 'brown seaweed' with 'antioxidant activity' and 'oxidative stress' further emphasizes the taxonomic and biochemical specificity of the studies,

particularly in elucidating polysaccharide- and polyphenol-driven pathways.

Notably, 'plant growth' serves as a hub connecting applied agronomic outcomes (yield enhancement) to molecular responses, validating seaweed extracts' dual role as growth promoters and stress alleviators. However, the limited integration of terms like 'nutrient uptake' within this network suggests a research gap in understanding ecological interactions beyond direct phytochemical effects. Corsi *et al.* (2022) reported the shift in biostimulant research from yield-focused goals (pre-2013) to stress resilience and quality enhancement due to sustainability needs amid climate change. Uses of traditional materials, like *Ascophyllum nodosum* extracts, are now being mixed with microbial biostimulants to understand soil-plant interactions. However, limited references to 'soil microbiome' and 'nutrient uptake' in our network revealed the gaps in research based on ecological mechanisms. These findings affirm the field's emphasis on stress physiology and biochemical validation; however, they also require expanded interdisciplinary studies to optimize seaweed-based solutions for sustainable agriculture under diverse environmental conditions.

Relevance degree (centrality) and development degree (density)

The chart analysis (Figure 1) categorized research themes on seaweed's effects on crop plants based on relevance degree (centrality) and development degree (density). Motor themes, such as 'seaweed extract plant growth' and 'seaweed extracts,' occupy the highest centrality and density, reflecting their maturity and vital roles in current agronomic research, particularly in validating growth and stress-resilience improvement across tomatoes and cereal crops. The considerable centrality of these themes underscores their integration with core agricultural priorities, such as yield optimization and the reduction of sustainable input. Berbeć (2024) reported a change in agriculture, moving from focusing solely on crop production (pre-2013) to emphasizing quality and resilience to abiotic stress

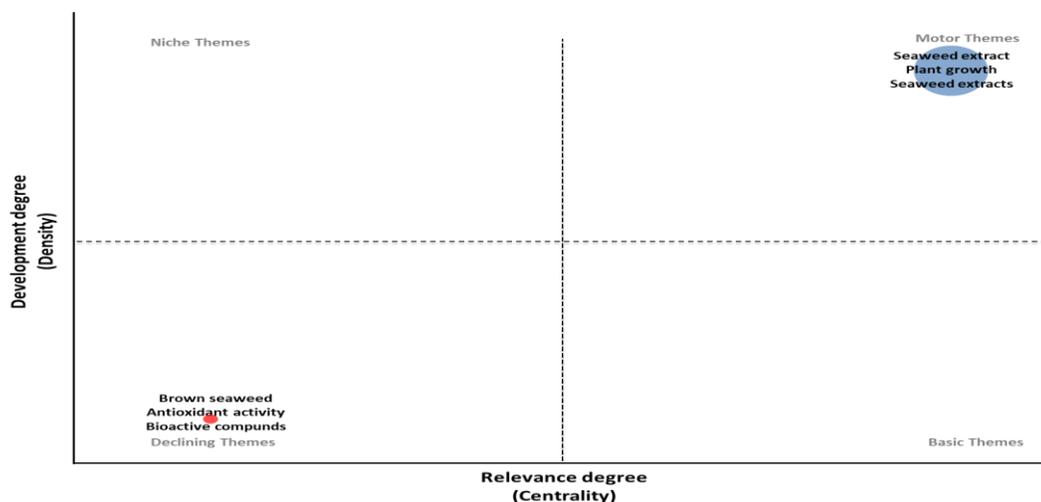


Figure 1. Mapping analysis based on Relevance Degree (Centrality) and Development Degree (Density).

conditions, motivated by the need for sustainability. In contrast, declining themes like 'brown seaweed antioxidant activity' and 'bioactive compounds' exhibited reduced density, signaling less focus on taxonomic-specific phytochemical profiling despite their antioxidative activity and taxonomic traits, whereas the contemporary research converges on applied climate adaptation. Basic themes, though underrepresented in the chart, likely encompass foundational concepts, i.e., nutrient uptake and soil health, which remain crucial. However, they need further conceptual and methodological development. The limited density of ecological and molecular interaction studies (rhizosphere microbiome modulation and gene regulation) highlighted the gaps in bridging field applications with systems-level understanding. The said analysis stressed the field's emphasis on applied biostimulant validation while urging interdisciplinary efforts to address the underdeveloped areas, such as molecular pathways and scalability challenges, to advance the seaweed-based solutions in global agriculture.

Factor analysis

Factor analysis of keyword clusters revealed two primary dimensions shaping research on the effects of seaweed on crop plants. Growth

historical significance in early mechanistic studies.

Segaran *et al.* (2024) contextualize this decline—their co-citation clusters showed early mechanistic studies prioritizing

and application bore dominance from terms with the highest positive loadings, including chlorophyll content, plant height, and foliar application, underscoring the focus on seaweed extract-driven improvement in photosynthetic efficiency, biomass accumulation, and optimized delivery methods. This phenomenon gained support from past findings where seaweed extracts evidently increased chlorophyll content, which is crucial for photosynthesis (El-Kaoaua *et al.*, 2013). For instance, the application of the green algae species *Ulva rigida* resulted in a 2.15-fold increase in total chlorophyll compared with the control plants. Similarly, Patil *et al.* (2025) emphasized the role of biostimulants in improving nutrient uptake, plant growth and development, and stress resilience in horticultural crops. Their review highlighted how biostimulants enhanced physiological and biochemical functions, contributing to increased yield and reduced dependency on chemical inputs.

Stress and biochemistry contrast with negative loadings for antioxidant activity,

oxidative stress, and bioactive compounds, highlighting the positive role of brown seaweed *Ascophyllum nodosum* in mitigating abiotic stress conditions through ROS scavenging and amino acid modulation. The clustering of seaweed extract and plant growth near dry weight confirms their centrality in agronomic outcomes, while outliers, such as Basel, Switzerland, reflected the administrative noise. These dimensions illustrated the field's dual emphasis on the promotion of growth and stress-alleviation mechanisms, though the spatial separation between chlorophyll content and antioxidant activity suggests a need for integrative studies linking physiological gains to molecular pathways. This analysis advocates for multidimensional frameworks to advance the seaweed biostimulants from empirical validation to systems-level agricultural solutions.

Optimizing agricultural practices with seaweed extracts

The compiled studies demonstrated seaweed extracts, particularly those obtained from *A. nodosum*, considerably enhanced plant growth, stress resilience, and yield across diverse crops, including tomatoes, maize, strawberries, and wheat (Table 1). Foliar application (0.1%–0.5%) and soil drenches (0.5–2 g/L) of *A. nodosum* extracts also improved drought tolerance in citrus, enhanced carrot root yield by 15%–20%, and boosted strawberry productivity in multi-year field trials (Spann and Little, 2011; Alam *et al.*, 2013; Ali *et al.*, 2019). Likewise, *Cystoseira* spp. and *Ecklonia maxima* extracts showed promise in enhancing wheat root development and hydroponic lettuce's shelf life, respectively, via antioxidant activity and nutrient modulation (Miceli *et al.*, 2021; Elbakkosh *et al.*, 2022).

The diverse bioactive compounds largely drive the enhancement of crop productivity through seaweed biostimulants. These compounds supply essential nutrients, activate antioxidant systems to mitigate drought and salinity stress, and heighten resistance to pathogens, while improving soil health through better structure, water retention, and microbial activity (Illera-Vives *et*

al., 2020; Nabti *et al.*, 2017; Sariñana-Aldaco *et al.*, 2025). Among them, *A. nodosum* is particularly effective, with alginic acid, fucoidan, and mannitol boosting antioxidant enzyme activity, osmolyte accumulation, and chlorophyll biosynthesis, thereby improving nutrient efficiency, stress resilience, and microbial interactions in the rhizosphere (Alí *et al.*, 2023; Kumari *et al.*, 2023; Patel *et al.*, 2023). Experimental studies also highlight dose-dependent and species-specific responses: moderate concentrations of *A. nodosum* and *Fucus vesiculosus* extracts enrich wheat and cucumber growth, while higher levels may inhibit development due to excess phenolics, and crops, like rice, respond more positively than cucumber under similar treatments (Shibaeva *et al.*, 2023; Thamvithayakorn *et al.*, 2024). Variability profoundly develops from the application method and environment: substrate treatments outperform seed coating in wheat; soil drenches are more effective for drought-stressed citrus; and conversely, foliar sprays (for example, 0.6% *Gracilaria* extract applied at critical growth stages) are most beneficial for crops like tomato and sunflower (Mutlu-Durak *et al.*, 2024; Osman and Salem, 2011).

Together, these findings underscore both the mechanistic basis and practical variability of seaweed-based biostimulants, confirming their potential as scalable tools for climate-resilient agriculture. However, the lack of standardized extraction protocols, inconsistent dose-response optimization across crops, and limited long-term or geographically diverse trials remain critical gaps. Addressing these issues will be essential to translate the promising outcomes of experimental and field studies into consistent, large-scale applications for sustainable agriculture (Ali *et al.*, 2021; Zhou, 2022).

Limitations and research gaps

Despite strong evidence of their benefits, seaweed biostimulants face limitations due to variable efficacy. This depends on species, concentration, and application method, making standardization difficult. For instance, *A.*

Table 1. Overview of seaweed extract applications in crop production.

No	Plant Species	Seaweed Species	Extract Type	Study Design	Measured Outcomes	Best Practices	Reference
1	Tomato, Sweet Pepper	<i>Ascophyllum nodosum</i>	Commercial, alkaline extract	Greenhouse and field experiments	Growth, yield, disease incidence	Foliar at 0.5% every 10 days is effective	(Ali <i>et al.</i> , 2019)
2	Maize (<i>Zea mays</i> L.)	<i>Laminaria</i> ; <i>Ascophyllum nodosum</i>	One <i>Laminaria</i> , five <i>Ascophyllum</i> extracts	Pot/Greenhouse	Root growth, nutrition, sugar accumulation	Use of FT-IR/FT-Raman to profile extracts	(Ertani <i>et al.</i> , 2018)
3	'Hamlin' Sweet Orange nursery trees	<i>Ascophyllum nodosum</i>	Commercial extract	Greenhouse/Container	Growth under drought, physiology	Soil drench superior to foliar for drought	(Spann and Little, 2011)
4	Carrot (two cultivars)	<i>Ascophyllum nodosum</i>	Soluble powder extract	Field trials	Root, yield, soil microbial activity	Weekly or biweekly at 0.5–1 g L ⁻¹ effective	(Alam <i>et al.</i> , 2014)
5	Strawberry (multiple cultivars)	<i>Ascophyllum nodosum</i>	Soluble extract powder (SAEP)	Greenhouse and field	Plant and fruit growth/yield, microbiome	Application at 1–2 g L ⁻¹ , weekly or biweekly	(Alam <i>et al.</i> , 2013)
6	Strawberry. Albion	<i>Durvillaea potatorum</i> , <i>Ascophyllum nodosum</i>	Commercial extract (Seasol®)	Field (Australia)	Yield, revenue, post-harvest rot	Combined drench + foliar effective; monthly	(Mattner <i>et al.</i> , 2023)
7	Strawberry (<i>Fragaria ananassa</i>)	<i>Ascophyllum nodosum</i>	Acadian LSC (commercial)	6-year commercial field trials	Yield, early growth, pest, disease	Regular soil application effective	(Holden and Ross, 2017)
8	Tomato, Eggplant seedlings	<i>Ascophyllum nodosum</i> (commercial)	Not specified	Seedling trays (two regions, Brazil)	Growth, physiological parameters	Both irrigation + foliar at 0.1%–0.3% are effective	(Villa-e-Vila <i>et al.</i> , 2024)
9	Leaf lettuce (hydroponics)	<i>Ecklonia maxima</i>	Basfoliar Kelp (commercial extract)	Hydroponics, floating system	Growth, yield, shelf life, WUE, etc.	Pre-harvest at 2–4 ml L ⁻¹ is beneficial	(Miceli <i>et al.</i> , 2021)
10	Ornamental sunflower	<i>Ascophyllum nodosum</i>	Commercial biostimulant	Greenhouse/lab	Germination, seedling growth	Avoid over- or under-dosing; moderate best	(Santos <i>et al.</i> , 2019)
11	Wheat (<i>Triticum aestivum</i> L.)	<i>Cystoseira crinitophylla</i>	Cold/hot/ethanol extracts, powder	Lab + pot experiment	Germ., growth, photosynthesis pigments	5%–10% extract is best; avoid high conc	(Elbakkosh <i>et al.</i> , 2022)
12	Pot marigold (<i>Calendula officinalis</i> L.)	Not specified (commercial seaweed)	Commercial	Field (two seasons)	Yield/ornamental traits, nutrients	Foliar 1500 ppm/soil 500 ppm optimal for traits	(Emam <i>et al.</i> , 2016)
13	Five woody species (seedlings, Italy)	<i>Ascophyllum nodosum</i>	Pure extract	Nursery tray + transplant	Biomass, leaf area, root length, gas exchange	Best dose varies; effect strongest at 1×/2× label	(Comin <i>et al.</i> , 2024)
14	Wheat (<i>Triticum durum</i>)	<i>Cystoseira barbata</i>	Water/alkali/acid extracts	Lab/greenhouse	Seedling growth, root morphology, minerals	Substrate application more effective than seedcoat	(Mutlu-Durak <i>et al.</i> , 2024)
15	Tomato (germination under salinity)	<i>Ascophyllum nodosum</i> / <i>Sargassum</i> spp.	Algut Super, Alga 300 (commercial)	Lab	Germination speed, % vigor, shoot/root	Soaking seeds in extract (1%–3%) effective under salt	(Papoui and Koukounaras, 2025)
16	Green gram	<i>Kappaphycus</i> , <i>Gracilaria</i>	Seaweed sap	Field (pre-kharif, India)	Yield, quality, nutrient uptake	Highest conc (15%) + fertilizer most effective	(Biswajit <i>et al.</i> , 2013)
17	Spinach (greenhouse)	<i>Ecklonia maxima</i> , <i>Ascophyllum nodosum</i> , plant/botanical	Extracts/comparative	Greenhouse; comparative	Yield, bioactives, mineral content	Foliar at 3 ml L ⁻¹ ; multiple biostimulant sources effective	(Rouphael <i>et al.</i> , 2018)
18	Thyme (<i>Thymus vulgaris</i>)	Not specified (seaweed extract)	Not specified	Field (sandy soil, Egypt)	Growth, oil, biochemicals	Foliar at 6 ml L ⁻¹ most effective	(Waly <i>et al.</i> , 2020)
19	Wheat (two varieties)	Not specified	Not specified	Field (Iraq)	Growth, yield	2 g L ⁻¹ foliar, repeated applications	(Al-Hasany <i>et al.</i> , 2019)
20	Rice	<i>Kappaphycus</i> , <i>Gracilaria</i>	Seaweed sap extract	Field (summer, India/Bangladesh)	Yield, straw, nutrient uptake	15% + fertilizer most effective	(Biswajit <i>et al.</i> , 2013)
21	Sunflower	<i>Ulva lactuca</i> , <i>Gracilaria dendroides</i>	Extracts	Field (Egypt)	Growth, yield, oil, nutrient content	0.6% <i>Gracilaria</i> extract, 3 app. at critical stages	(Osman and Salem, 2011)
22	Sugarcane	Not specified	Seaweed formulations	Field	Growth, yield, quality	1 ml L ⁻¹ LBS 6 best among tested	(Gomathi <i>et al.</i> , 2017)
23	Tomato (Piccolo F1)	<i>Ascophyllum nodosum</i> (L.)	Not specified	Factorial, greenhouse + field	Vegetative, yield parameters, chlorophyll	Dose × environment interaction, 0.3% in greenhouse best	(Koyama <i>et al.</i> , 2012)
24	Green onion (<i>Allium cepa</i> L.), cultivar Crystal	Not specified	Commercial seaweed extract (super 50)	Randomized complete block design (RCBD) with three replications	Tubular leaf count, bulb width, bulb length, vegetative growth, growth rate, bulb yield	Combined foliar application of humic acid (2 ml L ⁻¹) and seaweed extract (2 ml L ⁻¹) enhances growth metrics without yield compromise	(Al-Zubaidy, 2024)
25	Olive saplings (<i>Olea europaea</i> L.)	<i>Ascophyllum nodosum</i> (Acadian extract)	Acadian seaweed extract + organic humic acid	Field experiment	Main stem height, diameter, leaf number, leaf area, chlorophyll content, dry weight (vegetative parts and roots)	Foliar application of 1000 mg L ⁻¹ Acadian + 1000 mg L ⁻¹ humic acid maximizes growth traits (stem height: 131 cm, leaf area: 689 cm ² , root dry weight: 28.33 g)	(Abd <i>et al.</i> , 2025)

nodosum is effective at 0.3%–0.5% in tomatoes but requires higher doses for carrots and strawberries. Furthermore, soil drenches outperform foliar sprays in drought-stressed citrus, while the reverse is true for tomatoes and sunflowers. Such variability highlights the sturdy influence of crop type and environmental context. Most studies are short-term and geographically concentrated, with limited representation from Africa and Latin America and few long-term field trials to evaluate sustainability. Reliance on commercial formulations with undisclosed extraction methods further constrains reproducibility and mechanistic understanding. Moreover, the scientometric approach itself introduces limitations, as analyses based on Scopus, ScienceDirect, and Web of Science may exclude regional or non-English studies, while paywall restrictions and citation-based biases favoring established journals can reduce comprehensiveness. Addressing these gaps through standardized protocols, cross-crop dose-response trials, long-term monitoring, and broader data inclusion will be critical to advance seaweed biostimulants from experimental validation to scalable, evidence-based agricultural applications.

CONCLUSIONS

This scientometric-systematic review underscores the significant role of seaweed-derived biostimulants, particularly from *Ascophyllum nodosum*, *Ecklonia maxima*, and *Gracilaria* spp. in enhancing crop productivity, stress tolerance, and sustainable agricultural outcomes. As research has evolved from basic taxonomic and biochemical studies to applied agronomic applications, critical challenges remain, including the lack of standardized extraction protocols, limited understanding of molecular and ecological mechanisms, and insufficient scalability across diverse agroecosystems. Addressing these gaps requires future studies to prioritize the standardization of formulations, adopt multi-omics approaches to elucidate mechanisms of action, expand long-term and field-based trials, explore synergistic combinations with

other biostimulants, and develop affordable, farmer-friendly application methods. Equally important, policy frameworks must be up-to-date to support the regulation, quality assurance, and responsible use of biostimulants; agricultural extension services should promote education and best practices; and public–private partnerships are essential to scale innovations and reach smallholder farmers. By integrating scientific advancements with supportive policies and practical adoption strategies, seaweed-based biostimulants can become a pivotal tool in advancing climate-resilient and low-input agricultural systems.

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