Unlocking the potential of

SEAWEED BIOSTIMULANTS IN AGRICULTURE

for plant and soil health

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The Nature Conservancy

HATCH BLUE

WORLD BANK GROUP

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Cover photo: Seaweed harvest, Pemba Island, Tanzania. Photo by Roshni Lodhia, © TNC.

Back cover photo: Harvesting seaweed in southern Indonesia. Photo by Robert Jones, © TNC.

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Acknowledgments

This white paper was prepared in response to the requirements and aspirations voiced at a convening of industry, research, and government professionals in Washing-ton, DC, U.S., from October 23-24, 2025, organized by The Nature Conservancy, The World Bank, and Hatch Blue. See Appendix A for the full list of participants. One objective of this roundtable was to enhance understanding and facilitate knowledge exchange regarding the opportunities and challenges inherent in establishing a robust global seaweed biostimulant market and industry. Another was to begin identifying priority interventions. Accordingly, this white paper presents an overview of the advantages of seaweed biostimulants and outlines the benefits they offer to agriculture and regional economies. It aims to equip farmers, researchers, and policymakers with the knowledge to realize this potential, providing a structured roadmap for integrating seaweed biostimulants into sustainable agricultural practices.

We express our sincere gratitude to each of the roundtable participants and to the many individuals and companies whose generous contributions of time and resources enabled these discussions to take place.

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BUILDERS VISION

KWPF Korea-World Bank Partnership Facility

Acronyms

ASC	Aquaculture Stewardship Council International
CAGR	compound annual growth rate
CAP	common agricultural policy
CO_2	carbon dioxide
EBIC	European Biostimulants Industry Council
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
LCA	life cycle assessment
MSC	Marine Stewardship Council
R&D	research and development
SDG	Sustainable Development Goal
TNC	The Nature Conservancy
U.S.	United States
USD	U.S. dollar
USDA	U.S. Department of Agriculture

1. Executive summary

Seaweed biostimulants are substances derived from seaweed that promote plant productivity by improving nutrient uptake and resilience to stressors. Unlike conventional fertilizers, biostimulants activate plants' natural mechanisms rather than directly providing nutrients, offering the potential for additional economic, agricultural, and environmental benefits.

First, the economic benefits: a recent report by DunhamTrimmer (2025) suggested that the global seaweed biostimulants market is valued at over USD 1.4 billion, with a forecast of potential growth to over USD 2.4 billion by 2030. This expansion presents substantial opportunities for job creation, particularly in coastal regions.

Second, agricultural benefits include marked productivity enhancements. Numerous scientific studies have demonstrated that applying seaweed extracts enhances plant growth, vitality, and resistance to environmental stresses, resulting in substantial increases in overall plant productivity. Increases in yield ranging from 5% to 200% have been reported, depending on crop type and environmental conditions (e.g., Ali et al., 2021; Arias et al., 2024; Deolu-Ajayi et al., 2022; Goñi et al., 2021). Biostimulants bolster plants' resistance to drought, salinity, and extreme temperatures, and they contribute to soil health by improving structure, water retention, and microbial activity. Moreover, biostimulants may be used to reduce reliance on synthetic fertilizers and pesticides, enhancing sustainability and aligning agriculture with climate-smart initiatives.

Third, significant environmental advantages are associated with seaweed biostimulant use. By enhancing nutrient uptake, these products can reduce reliance on conventional fertilizers, thereby potentially lowering carbon dioxide (CO_2) emissions throughout the supply chain. Research indicates that the carbon footprint of seaweed biostimulants is substantially lower than that of traditional fertilizers (Gopalakrishnan & Ghosh, 2022). Recent studies from India have demonstrated that seaweed extracts can lead to considerable reductions in CO_2 emissions, with evidence showing up to a 50% decrease (260 kg CO_2 equivalents per hectare per week) in sugarcane cultivation compared to using synthetic fertilizers alone (Singh et al., 2018), and reductions of approximately 35 kg CO_2 equivalents per tonne in rice production (Sharma et al., 2017). Additionally, the farming of seaweeds as biostimulants, when farmed well, can support and improve ocean ecosystem services, such as nutrient removal and habitat provisioning. It can also help mitigate coastal acidification and create biodiversity benefits (Alleway et al., 2019; Gentry et al., 2020; The Nature Conservancy, 2021).

While most current production relies on select wild seaweed harvests, research (European Biostimulants Industry Council, 2023) indicates that a broad range of other brown, red, and green seaweeds exhibit biostimulant properties. Due to global declines in wild seaweed populations and necessary caps on harvests to ensure wild seaweed populations continue, the long-term expansion of wild harvesting for commercial purposes may be viewed as unsustainable, necessitating a transition toward aquaculture to ensure a scalable and reliable supply. Seaweed aquaculture occurs globally from Asia to North America, and there is worldwide potential for sustainable commercial production of biostimulants. Production models vary from simple farming models that supply just raw material to fully integrated systems encompassing production, processing, and distribution.

Major obstacles to scaling up commercial biostimulant production include complex regulations, the perception of higher product costs compared to synthetic options, varying quality and effectiveness, the lack of universal certification and quality standards, and farmer hesitation without proof of demonstrated value. Addressing these issues requires focused government and investor support, streamlined regulations, targeted research and development (R&D) funding, and investments in supply chains and technology. Incentives like subsidies, tax credits, and environmental programs help reduce adoption costs and demonstrate benefits. Growth depends on seaweed suppliers and biostimulant producers proving consistent quality at scale and buyers providing clear requirements.

These challenges can be met by pursuing five key recommendations, which focus on immediate needs and urge collaboration among agricultural and aquacultural stakeholders, government authorities, and private investors:

- **Review, revise, and streamline regulatory frameworks** and permitting processes to clarify expectations, reduce barriers, and ensure regulation is "fit for purpose."
- **Invest in targeted R&D** to optimize cultivation techniques, demonstrate product efficacy, identify crop and product specializations, promote innovation, and refine and optimize processing technologies.
- **Support the establishment of key infrastructure and capabilities**, including nursery facilities that ensure contaminant-free and biosecure seedstock where these do not exist, as well as processing facilities and biorefineries.
- **Actively enable and support collaboration** across the value chain (agriculture, aquaculture, processors, suppliers, and government).
- **Implement financial incentives** at multiple scales to drive broader adoption. These might include incentives for investors to highlight sustainability improvements, for regional governments to support start-up development of sustainable industries, for land-based farmers to test and validate product performance benefits, and for seaweed farmers to refine product specificity and increase market access and marketing.

Tables 1 and 2 offer a more detailed roadmap for taking action over the short, medium, and long terms, while Appendix B describes the anticipated outcomes and outputs.

In conclusion, while the sector holds significant promise for scaled agricultural benefits and in-water benefits from increased seaweed aquaculture, realizing the full benefits of seaweed biostimulants in supporting sustainable agriculture will depend on deliberate, synchronized action across government, industry, and the research community to overcome present challenges and unlock future potential.

Harvesting seaweed in Belize. Photo by Julie Robinson, © TNC.

Seaweed biostimulants roadmap:

IMMEDIATE PRIORITIES FOR ACTION

Table 1. Year 1 strategic priorities and actions for R&D.

Year 1 short-term priorities and actions
Connect the community.
▪ Facilitate collaboration between aquaculture, agriculture, government, and research partners to set R&D priorities. ▪ Clarify farmers' needs and expectations. ▪ Identify and engage stakeholders. ▪ Put in place communication strategies. ▪ Identify sharable information and develop and establish knowledge-exchange networks/approaches. ▪ Hold a second roundtable to set priorities for the White Paper Work Plan.
Develop products and the market overall.
▪ Collate and share data on seaweed biostimulant product performance. ▪ Validate effectiveness and identify gaps (in species, crops, and traits) for further R&D. ▪ Identify additional knowledge gaps in product efficacy and the supply chain. ▪ Initiate market and supply chain analyses. ▪ Assess government incentives/grants and novel finance approaches and suggest improvements to support industry growth, including blended finance mechanisms. ▪ Identify and disseminate funding opportunities. ▪ Develop strategies to reduce reliance on imports and strengthen domestic supply chains. ▪ Define key traits in current biostimulants and outline R&D to optimize them or discover new species.
Develop capacity and capability.
▪ Specify R&D needs to support transfer from wild harvest to aquaculture and ensure reliable, biosecure seedstock. ▪ Assess workforce skill gaps and create a capacity-building plan.
Enhance governance (regulatory and policy frameworks).
▪ Develop a plan for the delivery of product standards, standardized testing, and traceability protocols. ▪ Address gaps in certification schemes to enhance credibility and access to the market for premium seaweed products. ▪ Recommend a simplified permitting approach. ▪ Review the integration of biostimulants into credit systems.
Advance a sustainability proposition.
▪ Compile sustainability data to assess biostimulant effectiveness and knowledge gaps. ▪ Propose improved methods for measuring sustainability benefits and research life cycle assessment (LCA) options. ▪ Evaluate the benefits of additional environmental sustainability options (e.g., credit systems).

Seaweed biostimulants roadmap:

MEDIUM- TO LONG-TERM PRIORITIES FOR SCALE

Table 2. Years 1–5 strategic priorities and actions for R&D and establishing a long-term value proposition.

Priorities and actions	
Years 1-3 — medium term	**Years 3-5 — long term**
Connect the community.	
▪ Establish ongoing collaboration with subgroups in strategic development areas and establish R&D review structures. ▪ Develop a shared method/mechanism to relate the cost-benefit and return on investment implications for seaweed and land-based farmers to guide priorities and investment. ▪ Form key working groups to boost collaboration and innovation.	▪ Review the collaboration structure to consider next-stage strategic R&D. ▪ Work with stakeholders to create a universal business development plan that helps operators individually grow while supporting a thriving stakeholder community.
Develop products and the market overall.	
▪ Develop a performance reference and research database and templates for biostimulant R&D outputs, with simple-language summaries. ▪ Initiate and launch a 5-year R&D plan targeting product improvement, performance, and new species exploration. ▪ Develop and implement a sector growth plan to improve the financing model, including government incentives and industry development grants. ▪ Initiate a trait optimization and bioprospecting R&D plan. ▪ Begin developing and testing better extraction and processing methods to maximize bioactive compounds/key traits.	▪ Conduct next-level studies to understand the modes of action for biostimulants. ▪ Conduct R&D to understand biostimulant impact on plant health under stress conditions to further boost plant health, yield, and stress tolerance, and to support global food security. ▪ Implement and scale evidence-based educational programs that inform farmers about the benefits and usage of seaweed biostimulants, facilitating greater market acceptance. ▪ Encourage investment with new finance approaches, including slow capital.
Develop capacity and capability.	
▪ Develop evidence-based geography and crop-specific educational programs that inform farmers about the benefits and usage of seaweed biostimulants.	▪ Establish long-term, biosecure processes for the seedstock supply and hatchery networks to ensure a reliable and scalable seaweed supply. ▪ Update and scale better practice standards for the cultivation of key seaweed species (open-water and land-based) to support and build industry expertise.

<table>
<tr><th colspan="2">Priorities and actions</th></tr>
<tr><th>Years 1-3 — medium term</th><th>Years 3-5 — long term</th></tr>
<tr><th colspan="2">Develop capacity and capability, continued.</th></tr>
<tr><td>▪ Create and apply better practice standards for cultivating key seaweed species (open-water and land-based) to be used as templates for subsequent species and for scaling high-quality products.
▪ Initiate an aquaculture seedstock supply plan that ensures biosecurity.
▪ Initiate a workforce capacity-building plan and start workforce training programs for sector innovation and expansion.
▪ Conduct a desktop evaluation of biorefinery extraction options, systematically assess these options, align them to the appropriate industry scale, and create a development plan.</td><td>▪ Implement a collaborative approach to providing access to education and training in seaweed aquaculture and biotechnology.
▪ Implement advanced biorefinery extraction processes to drive large-scale growth and maximize resource value.</td></tr>
<tr><th colspan="2">Enhance governance (regulatory and policy frameworks).</th></tr>
<tr><td>▪ Create a draft plan for a unified market and draft product standards for seaweed biostimulants to ensure consistent, clear regulations.
▪ Recommend a simplified permitting approach and streamline existing permits to improve efficiency and reduce entry barriers.
▪ Review how biostimulants could be integrated into governments' environmental credit systems.</td><td>▪ Establish agreed-upon, dependable, and effective regulatory standards that promote seaweed biostimulants widely across agricultural sectors.</td></tr>
<tr><th colspan="2">Advance a sustainability proposition.</th></tr>
<tr><td>▪ Develop and grow the portfolio of sustainability and LCA analyses to reinforce the environmental value of seaweed biostimulants.
▪ Pursue additional environmental sustainability options (e.g., credit systems).</td><td>▪ Evaluate the broader ecological benefits and potential impacts of expanded seaweed cultivation for biostimulants.
▪ Develop and implement payments for ecosystem services and crediting schemes to validate and support both the in-water and on-land benefits of seaweed biostimulants.</td></tr>
</table>

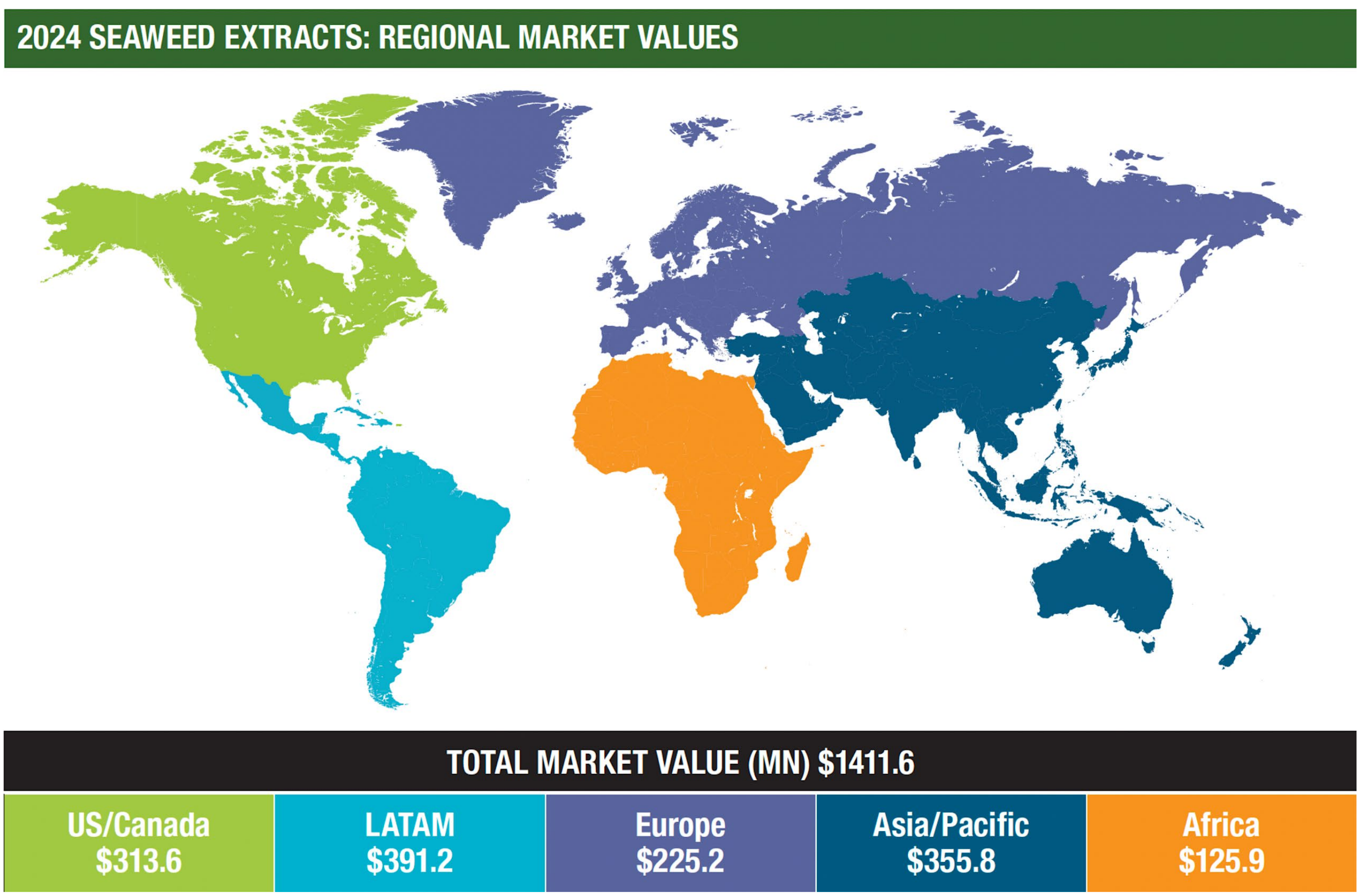
2. Introduction

With the global population projected to increase by 2 billion by 2050 (Daszkiewicz, 2022), agriculture faces mounting demand for higher crop yields and improved quality. Biostimulants represent a sustainable option and offer compelling investment opportunities for stakeholders in both the public and private sectors. Biostimulants have become important assets for improving resilience in both agricultural crops and farming systems (European Biostimulants Industry Council [EBIC], 2023; Price et al., 2024). Unlike fertilizers that provide direct nutrient input, biostimulants enhance the utilization of available nutrients and water. Their role in advancing sustainable food systems has been increasingly acknowledged, particularly through their positive impact on crop yield, quality, and resilience; the effectiveness of biostimulants is extensively supported by scientific research (Du Jardin, 2015; Mannino, 2025). Plant biostimulants deliver scientifically validated approaches designed to boost productivity and input efficiency, address environmental challenges, increase farm profitability, and support sustainable agricultural practices.

Seaweed-based biostimulants have been shown to have considerable advantages, such as improving nutrient use efficiency, stimulating plant growth, increasing stress tolerance, improving soil health, and enhancing water retention (Ali et al., 2021; Craigie, 2011; El Boukhari et al., 2020; Illera-Vives et al., 2020). Seaweed products have also been shown to improve fertilizer performance and enable access to previously unavailable soil nutrients, including enhanced phosphorus solubilization (Illera-Vives et al., 2020; Mondal et al., 2025). As a result, they help reduce nutrient losses and minimize environmental impacts and may help optimize the efficacy and efficiency of chemical fertilizers.

Currently, most seaweed used in biostimulant production is sourced from wild harvesting, which may have long-term supply limitations. Consequently, future market growth will require aquaculture initiatives.

Figure 1. Global seaweed biostimulant market for 2024 (DunhamTrimmer, 2025).



While seaweed farming is a common global industry, large-scale production of biostimulants via aquaculture is a relatively recent development.

The global market for seaweed biostimulant products is expanding quickly, with major growth predicted in the coming years. In 2023, the World Bank identified seaweed biostimulants as a primary area for short-term expansion and estimated the worth of the global seaweed biostimulant market at that time to be approximately USD 1 billion (World Bank, 2023). A recent market analysis report by DunhamTrimmer suggested that the current global market for seaweed biostimulants is over USD 1.4 billion (Figure 1) and may surpass USD 2.4 billion by 2030 (DunhamTrimmer, 2025).

Consequently, seaweed biostimulants represent a positive investment opportunity for both individuals and governments, with the potential to generate significant economic returns and new employment opportunities in coastal regions. Seaweed farming to support the biostimulants sector could play an important role in advancing sustainable livelihoods, upskilling communities, mitigating climate change, and bolstering food security (World Bank, 2023). Increased research and development (R&D) investment is needed to realize these opportunities.

This white paper offers a detailed analysis of the sector, assessing opportunities and hurdles in agriculture, seaweed farming, and investment, and it provides targeted recommendations for supporting industry growth. The document examines the advantages of seaweed biostimulants for agriculture alongside opportunities in seaweed cultivation and aquaculture. It also addresses challenges, like regulatory complexities and cost, and sets out policy and investment guidance focused on fostering sustainable development, innovation, and market growth. Additionally, it highlights the environmental and economic benefits of seaweed biostimulants in promoting worldwide sustainable agriculture.

This white paper has been structured to target two specific audiences:

1. **Agricultural farmers and corporate end users** examining seaweed biostimulants to enhance traditional farming and improve sustainability
2. **Policymakers and investors** reviewing policy concerns and investment prospects

Key areas covered include the following:

- **Product definition and benefits**: Explanation of what seaweed biostimulants are, their differences from fertilizers and pesticides, and their impact on crops and soil health
- **Market opportunity**: Analysis of economic potential and regional markets
- **Production considerations**: Discussion of species choice, farming methods, processing technology, and quality control
- **Regulatory landscape**: Overview of fragmented and inconsistent international regulations and policies, and the push for harmonization

Kenya seaweed aquaculture. Photo by Hannah Packman, © TNC.

- **Sustainability impact**: Examination of environmental benefits like decreased use of chemicals, lower carbon emissions, and ecosystem services
- **Investment opportunity**: Exploration of how government and private funding can drive development and deliver social and environmental gains

This white paper serves as a foundation for global, regional, and national strategic planning, policymaking, and investment decisions in the growing seaweed biostimulants sector.

3. Seaweed biostimulants: Opportunities in agriculture

3.1. Sector overview and background

Meeting the projected demands of a growing global population will require a significant increase in food production by 2050 (Daszkiewicz, 2022). A number of approaches can address this demand, and biostimulants can be an important tool for farmers. Many studies have shown that the use of biostimulants can increase quality and performance across a range of crops (Table 3). However, seaweed extracts have positive effects on more than just plant growth. They can also improve stress resilience and increase soil health (Ali et al., 2021), enabling farmers to get more out of their current farming strategies and providing increased climate resilience and crop stability.

However, to improve capacity sustainably, more than just an increase in overall production is necessary. The effectiveness and efficiency of current farming practices must be improved by reducing waste, shortening supply chains, and building resilience into food production systems. The challenges confronting food production systems, including those arising from climate change, population insecurity, limited freshwater resources, and soil degradation, may be mitigated, in part, by incorporating seaweed-derived biostimulants.

Table 3. Selected studies demonstrating specific benefits and crop applications, updated with permission from the U.S. Department of Agriculture (USDA) and adapted from Price et al. (2024).

	Learned benefit of seaweed-based biostimulant application			
Crop name	Germination/ growth efficiency	Improved yield/ quality	Abiotic stress resistance	Abiotic stress — manipulated
Apple		Mousavi et al. (2024)		
Grape	Frioni et al. (2021)	Arioli et al., (2021), Frioni et al. (2018, 2019), and Leogrande et al. (2022)		Frioni et al. (2021)
Lettuce	Chaski and Petropoulos (2022), Di Mola et al. (2019), Moncada et al. (2022), Rasouli et al. (2022), Sandhu et al. (2018), Velasco-Clares et al. (2024), and Wang et al. (2022)	Di Mola et al. (2019, 2020) and Velasco-Clares et al. (2024)		Chaski and Petropoulos (2022)
Maize	Fayzi et al. (2020) and Trivedi, Vijay Anand, Vaghela, and Ghosh (2018)	Trivedi, Vijay Anand, Kubavat, et al. (2018); Trivedi, Vijay Anand, Vaghela, and Ghosh (2018); Trivedi, Vijay Anand, et al. (2022); and Trivedi, Kumar, et al. (2022)	Tinte et al. (2022) and Trivedi et al. (2021)	Kumar et al. (2020); Trivedi, Vijay Anand, Kubavat, et al. (2018); and Trivedi, Vijay Anand, et al. (2022)

	Learned benefit of seaweed-based biostimulant application			
Crop name	**Germination/ growth efficiency**	**Improved yield/ quality**	**Abiotic stress resistance**	**Abiotic stress — manipulated**
Oats		Gurmani et al. (2021)		
Pepper	Ali et al. (2022, 2023) and Ozbay and Demirkiran (2019)	Ali et al. (2022, 2023), Arthur et al. (2023), and Renaut et al. (2019)	Dalal et al. (2019)	
Potato	Gaynatulina and Khasbiullina (2021) and Wadas and Dziugieł (2019)	Wadas and Dziugieł (2019, 2020)		
Rice	Shahzad et al. (2023)	Shahzad et al. (2023)		Shahzad et al. (2023)
Soybean	da Silva et al. (2024); Kocira et al. (2018); and Mathur et al. (2015)	Franzoni et al. (2023); Kocira et al. (2018); Krawczuk et al. (2023); Łangowski et al. (2021); Mathur et al. (2015); and Meyer et al. (2021)	Shukla et al. (2018)	da Silva et al. (2024) and do Rosário Rosa et al. (2021)
Strawberry	Rana, Lingwal, et al. (2023) and Soppelsa et al. (2019)	Mattner et al. (2023); Rana, Lingwal, et al. (2023); Soltaniband et al. (2022); Soppelsa et al. (2019); and Weber et al. (2018)		
Tomato	Ali et al. (2022, 2023); Bentley et al. (2022); Borella et al. (2023); Domingo et al. (2023); González-González et al. (2020); Hernández-Herrera, Sánchez-Hernández, et al. (2022); Karthik and Jayasri (2023a); Mazepa et al. (2021); Moncada et al. (2022); Polo and Mata (2018); and Villa e Vila, Rezende, et al. (2023)	Abdelkader et al. (2021); Ahmed et al. (2023); Ali et al. (2023); Borella et al. (2023); Campobenedetto et al. (2021); Chanthini et al. (2019); Colla et al. (2017); Karthik and Jayasri (2023a); Lakshmi et al. (2023); Liava et al. (2023); Polo and Mata (2018); Renaut et al. (2019); Subramaniyan et al. (2023); Vaghela et al. (2023); Villa e Vila, Marques, et al. (2023); and Villa e Vila, Rezende, et al. (2023)	Carmody et al. (2020) and Zhang et al. (2023)	Ahmed et al. (2023); Ali et al. (2024); Borella et al. (2023); Campobenedetto et al. (2021); Domingo et al. (2023); Gil-Ortiz et al. (2023); Hernández-Herrera, Sánchez-Hernández, et al. (2022); Kalozoumis et al. (2021); Liava et al. (2023); Morales-Sierra et al. (2023); Top et al. (2023); Vaghela et al. (2023); and Villa e Vila, Marques, et al. (2023)
Wheat	Mohammed Ali and Mohammed (2024), Sooväli et al. (2018), and Stamatiadis et al. (2021)	Knapowski, et al. (2019), Matysiak et al. (2018), Sooväli et al. (2018), and Stamatiadis et al. (2021)		Sharma et al. (2019)

Note. See Appendix C for a more comprehensive list of crops.

Differentiation of biostimulants from biopesticides and biofertilizers

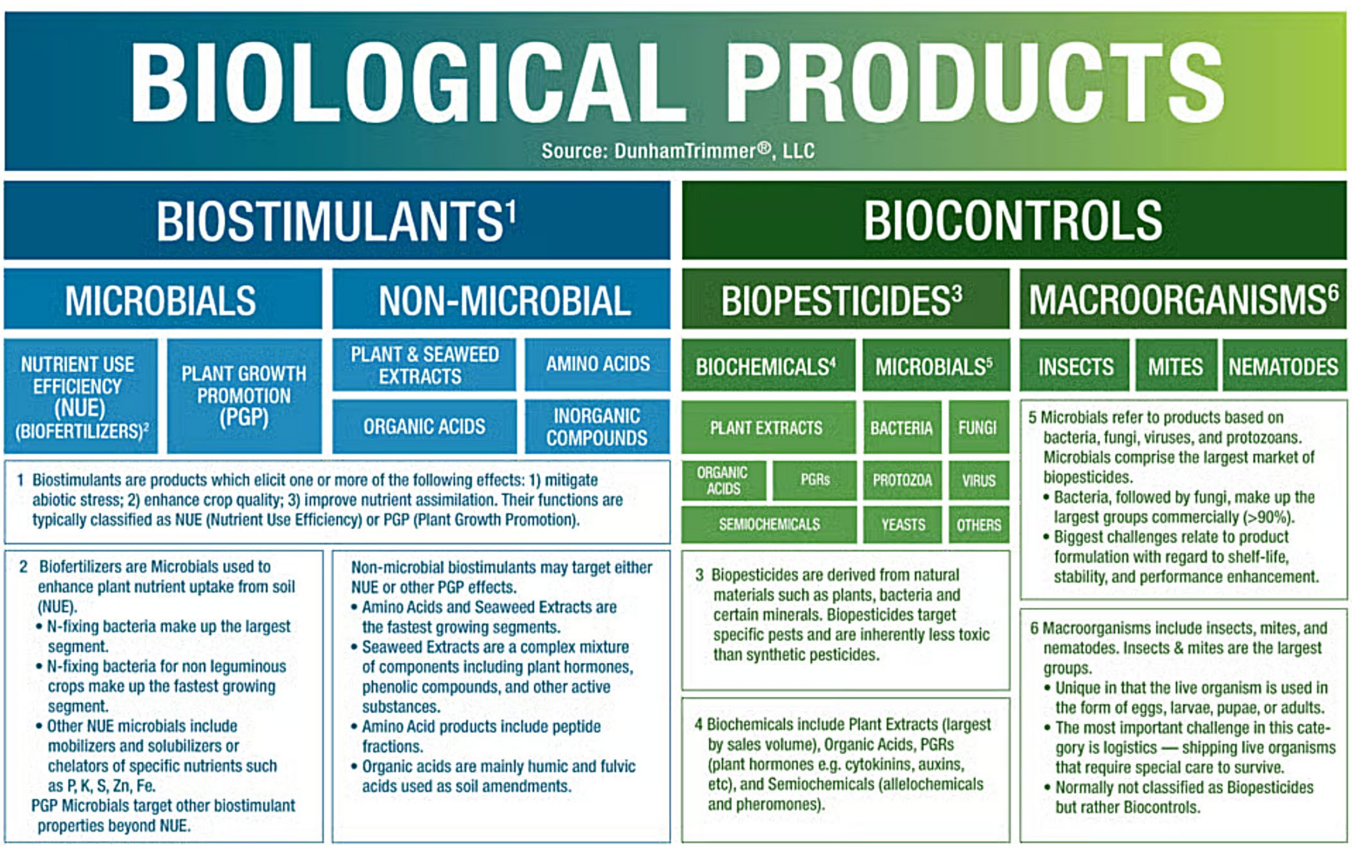
A range of bioproducts is used in agriculture for targeted and overlapping soil and plant health benefits. Generally, these products are used in combination on the farm to support and improve crop performance and management practices. Farmers often experience improved outcomes when they incorporate biostimulants alongside fertilizers and chemical-based pest control programs.

Figure 2 provides a useful summary of the distinctions between biostimulants and biopesticides.

Biostimulants can be defined as "biologically derived products that enhance productivity due to their unique mix of constituents, not just known nutrients or protective agents" (Yakhin et al., 2017). They boost efficiency in using nitrogen, phosphorus, and potassium, and they help absorb micronutrients. However, they differ from fertilizers in how they benefit plants: fertilizers supply nutrients directly, while biostimulants trigger plants' natural abilities for nutrient absorption and stress management without direct nutrient input. Both can improve growth and yield (EBIC, 2023).

In addition to the direct effects on plant growth, biostimulants have the potential to improve broader soil health, supporting or engaging soil microbial communities and adding a further benefit to application, one which can improve overall resilience and sustainability. Specific agricultural benefits include marked productivity enhancements, with yield increases ranging from 5% to 200%, depending on crop type and environmental conditions (e.g., Ali et al., 2021; Arias et al., 2024; Deolu-Ajayi et al., 2022; Goñi et al., 2021). Biostimulants bolster plants' resistance to drought (Goñi et al., 2018), salinity (Wahid et al., 2025), and extreme temperatures (Gardiner-Piggott et al., 2025). They contribute to soil health by improving structure, water retention, and microbial activity (Frioni et al., 2018; Khan et al., 2009). Moreover, seaweed biostimulants can reduce reliance on synthetic fertilizers and pesticides, enhancing sustainability and thus aligning well with climate-smart agricultural initiatives (Quille et al., 2025).

Figure 2. Definitions of biostimulants and biocontrols (Thomas, 2024).



The appeal of seaweed biostimulants lies in their combination of performance benefits and potential long-term gains in soil health and sustainability. Seaweed biostimulants can provide a useful additional tool for managing agricultural risk by building resilience in farming systems via greater supply chain options and nutrient alternatives. Aquatic-based products have long been used in agriculture, whether as fish waste added directly to the soil, seaweed laid as mulch around crops, or seaweed feed for livestock. Today's seaweed biostimulant market is reintegrating this knowledge into modern farming practices but needs the collaboration of seaweed farmers, biostimulant creators, and land farmers to get the products right and deliver the outcomes farmers want at a price they can afford.

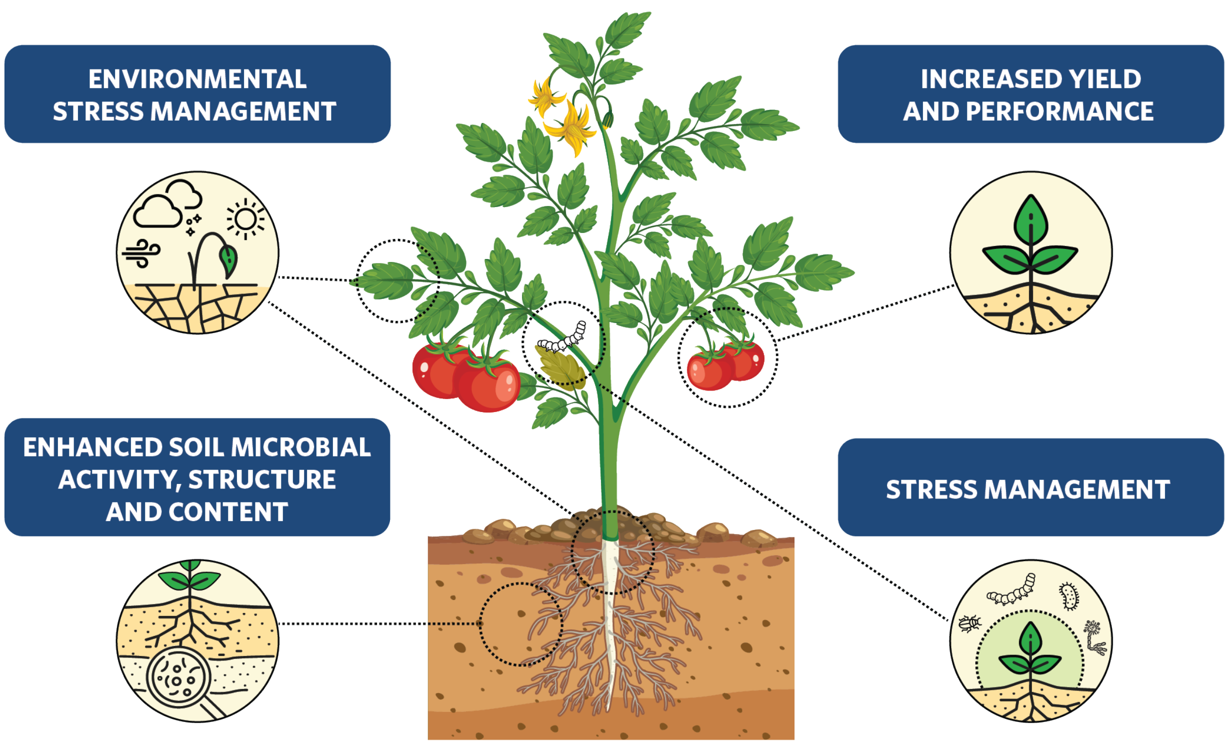
3.2. Applications in agriculture

The advantages of seaweed extracts (Figure 3) are being increasingly recognized, especially when applied in conjunction with chemical fertilizers. Integration with conventional fertilizers seems to augment their benefits, maintaining or improving crop yields and quality by supporting nutrient uptake, boosting micronutrient absorption, and increasing levels of protein, vitamins, and antioxidants in crops (Ali et al., 2021; Battacharyya et al., 2015; Craigie, 2011; Moradi & Siosemardeh, 2025; Stirk et al., 2020).

Seaweed extracts have been shown to boost plant growth, crop yield, and stress tolerance across a broad range of crops, including cereal grains, legumes, vegetables, fruits, and other horticultural species. See Table 3, or a more comprehensive list in Appendix C.

Seaweed-treated crops often show higher nutritional value and increased antioxidant levels, leading to yield improvements (Ali et al., 2021; Craigie, 2011). For example, recent trials with wheat reported yield increases of 16%–39% (Mondal et al., 2025), while trials involving the addition of seaweed biostimulants in Mexico found a 60% increase in premium-grade potatoes and in Brazil found 29%–65% productivity gains in coffee (AgFunderNews, 2025). In addition, studies have also shown that biostimulant application can provide benefits for seed priming, with increases in germination rates, seedling

Figure 3. Overview of the positive effects of seaweed extracts on plant and soil systems. © TNC.



growth, and antioxidant capacity. See Table 3, or a more comprehensive list in Appendix C.

The performance benefits and efficacy of seaweed biostimulants are now well documented (El Chami & Galli, 2020; Illera-Vives et al., 2020; Khan et al., 2009; Mughunth et al., 2024; Pereira et al., 2020; Stirk et al., 2020), although the specific mechanisms are not always fully understood due to their complexity (DunhamTrimmer, 2025). Substantial evidence demonstrates that biostimulants can mitigate abiotic stress across a variety of crops (Elumalai et al., 2025; Gardiner-Piggott et al., 2025; Mughunth et al., 2024).

In 2024, USDA released a comprehensive report on revenue generation and restoration for seaweeds and seagrasses, including a summary on existing studies that demonstrate the advantages of seaweed-based biostimulant applications across multiple performance metrics, including germination and growth efficiency, yield improvement, resistance to stress, enhancement of soil quality, and manipulation of abiotic stress (Price et al., 2024). These findings highlight the diverse applications and significant benefits associated with seaweed biostimulants (Table 3).

Seaweed extract application can also mitigate the impacts of environmental stresses, such as drought, salinity, and temperature, by improving soil structure and water retention, alleviating pressure on freshwater resources, and promoting microbial activity, making them especially useful in organic and regenerative agriculture systems. These combined production and environmental benefits substantially enhance the appeal of seaweed-derived biostimulants.

Recent research indicates that seaweed extracts might offer extra advantages by boosting systemic resistance, allowing plants to fortify their natural defenses against pests and diseases, and potentially reducing their dependence on synthetic pesticides. While promoting pest resilience is not the primary function of seaweed biostimulants, this supplementary advantage merits further investigation. When considered alongside their biostimulatory effects, seaweed extracts may present an organic and sustainable alternative to chemical pesticides, particularly in circumstances where chemical resistance poses a challenge (Tandathu et al., 2025; Vathshalyan et al., 2022).

Active ingredients and mode of action

Compared to other biostimulant sources, seaweed extracts have some of the most well-documented plant benefits, and polysaccharides unique to seaweeds may act as elicitors that encourage plant defense mechanisms, which can enhance the plants' stress tolerance (Figure 4; DunhamTrimmer, 2025).

While the benefits of biostimulants are clear—e.g., better nutrient absorption, increased resilience to stresses (like drought, salinity, and temperature), and improved crop yield and quality—the specific ways these results are achieved are not always fully understood (Navarro-León et al., 2022; Rouphael & Colla, 2020; Sujeeth et al., 2022). Further understanding the active ingredients in seaweed biostimulants and the mechanisms of interaction could help agricultural producers optimize their use for specific, targeted benefits, leading to more efficient and sustainable farming practices and the potential for reduced costs in other areas (Rabhi et al., 2025).

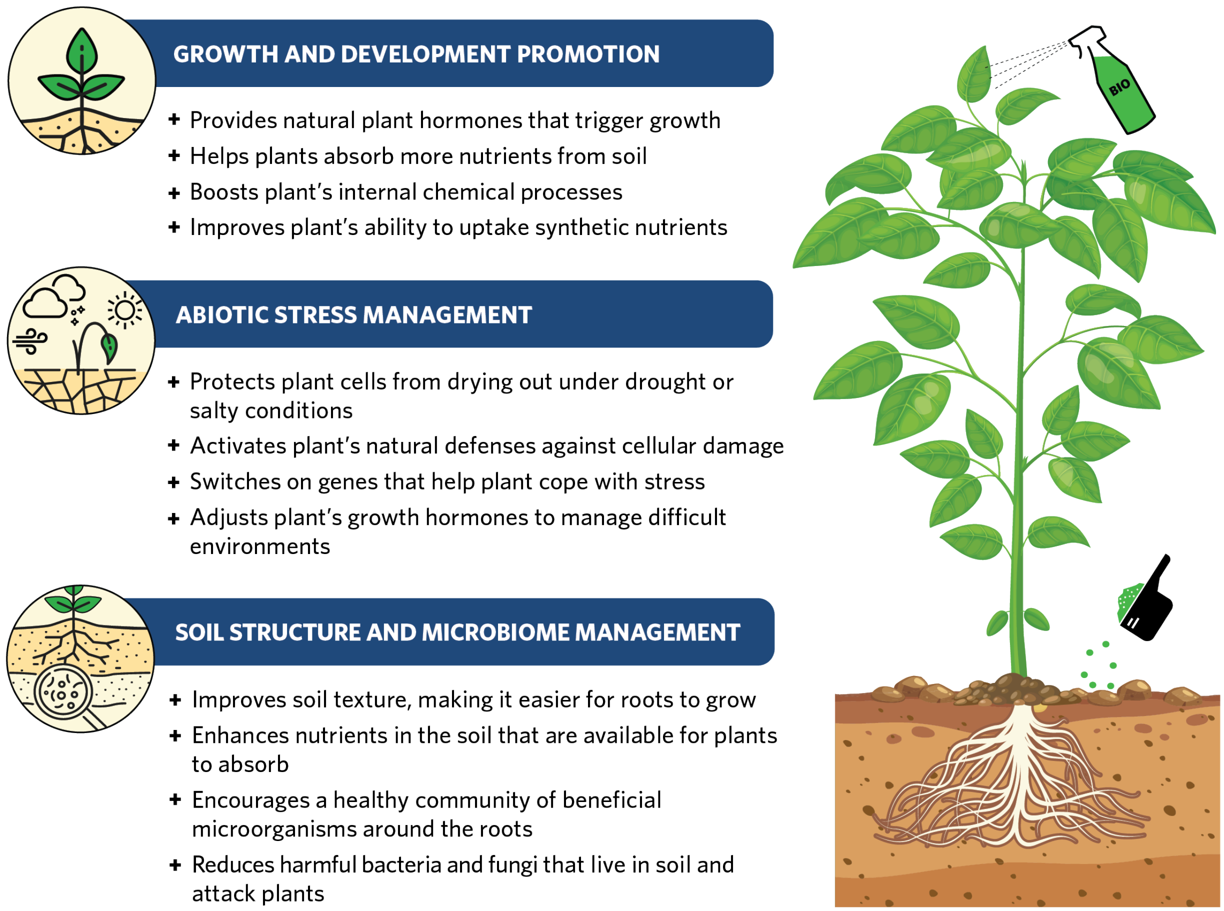
A thorough understanding of the active ingredients and modes of action enables the strategic use of seaweed biostimulants as reliable, scientifically supported tools to enhance crop resilience and productivity. By matching the biostimulant's ingredients with a crop's growth stage or environmental stress (like drought or salinity), producers can ensure the product delivers maximum value. This value, in turn, can justify the associated input costs.

Although pinpointing the exact mode of action will help refine and tailor these products going forward (Yakhin et al., 2017), it is not strictly necessary in the first instance if the overall benefit is understood. However, as regulations on agricultural inputs evolve, understanding the exact composition and which traits can be over- or under-expressed in particular species will ensure compliance with organic certifications or local environmental standards, which may provide a market advantage.

Methods of application

Seaweed-based biostimulants are typically applied via foliar sprays, soil amendments, or seed priming. Foliar application is the predominant method, with spraying generally scheduled to correspond with critical crop developmental phases, such as early vegetative growth, pre-flowering, or fruit set. Soil

Figure 4. Overview of the known mechanisms, or modes of action, by which seaweed extracts benefit plant and soil systems, adapted from Rabhi et al. (2025).



amendments are available in both liquid and powdered formats and are generally incorporated into or applied to the soil surrounding plant roots.

Sustainability benefits

Sustainability for agricultural farming

Although seaweed biostimulants offer advantages in all types of arable farming and horticulture, their highly organic composition makes them especially well-suited to organic agriculture and to environmentally sensitive and regenerative-agriculture regions. This composition emphasizes their special importance to contemporary sustainable farming practices.

Although synthetic chemicals provide cost-effective solutions for achieving high agricultural yields, their excessive or inappropriate application has been associated with persistent detrimental effects on both environmental and human health (de Vries, 2021; Dhankhar & Kumar, 2023; Goucher et al., 2017; Jwaideh et al., 2022; United Nations Environment Programme, 2023). Projections indicate that by 2050, one-third of the Earth's surface will surpass freshwater nitrogen thresholds harmful to ecosystems, and 7.6 million km^2 may experience nitrogen concentrations in drinking water that threaten human health (Atwood et al., 2025; Bodirsky et al., 2014). Consequently, environmental organizations, investors, and governments are increasingly focusing on these matters, which encourages farmers to look for eco-friendly options like seaweed extracts instead of traditional fertilizers.

Recent research demonstrates that farmers utilizing seaweed extracts can achieve greater financial returns (Arias et al., 2024; MacLaren et al., 2022; Mariano, 2018; Reddy et al., 2024) and better position themselves to reduce chemical input per crop (Moradi & Siosemardeh, 2025). These extracts are non-toxic, and their use—combined with reductions in conventional chemical applications—mitigates negative environmental impacts, thereby offering substantial sustainability benefits for agriculture and surrounding ecosystems. However, to drive adoption, it is crucial to demonstrate real performance advantages that can be achieved cost-effectively.

Sustainability of seaweed as a feedstock for biostimulants

Currently, most seaweed biostimulant products are derived from wild-harvested sources, particularly brown seaweeds and kelps, because they are easy to harvest in large quantities from coastal waters. However, numerous other seaweed species have demonstrated agricultural benefits (see Table 4), with many of these species cultivated for different purposes.

Wild harvesting carries a number of ecological risks: the potential to deplete stocks and disrupt habitats if harvesting is not carefully managed, resulting in inconsistencies in both biomass and quality (Kraan, 2020; Lauzon-Guay et al., 2021). In certain areas, sustainable harvesting from wild populations has proven effective, thanks to healthy wildlife numbers and solid regulatory systems. However, wild harvesting is, by necessity, limited. As demand grows, pressure on wild stocks may make the addition of seaweed farming essential. Seaweed farming, when farmed and sited well, has been demonstrated to provide nutrient removal, habitat provisioning, ocean acidification buffering, and other ecosystem service benefits (The Nature Conservancy [TNC], 2021).

3.3. Operational priorities and requirements

Factors influencing effectiveness

The efficacy of seaweed-based biostimulants is influenced by several variables (Ali et al., 2021):

- source species and growing conditions, such as location, season, and nutrient availability;
- extraction and processing approach (temperature, pressure, pH, solvents, enzymes);

Table 4. List of important seaweed species with documented biostimulatory properties, adapted from Ali et al. (2021).

Phaeophyceae	Rhodophyta	Chlorophyta
Ascophyllum nodosum	*Macrocystis pyrifera*	*Ulva lactuca*
Ecklonia maxima	*Porphyra perforate*	*Enteromorpha prolifera*
Durvillaea antarctica	*Nereocystis* spp.	*Caulerpa paspaloides*
Durvillaea potatorum	*Cyanidium caldarium*	*Ulva armoricana*
Fucus vesiculosus	*Gelidium serrulatum*	*Codium liyengarii*
Sargassum spp.	*Acanthophora spicifera*	*Codium tomentosum*
Hydroclathrus spp.	*Kappaphycus alvarezii*	*Caulerpa sertularioides*
Ralfsia spp.	*Gracilaria edulis*	
Laminaria digitata	*Gracilaria dura*	
Cystoseira myriophylloides	*Laurencia johnstonii*	
Fucus spiralis		
Padina pavonica		
Fucus gardneri		

- application method (soil, foliar spray, seed priming);
- timing and dosage; and
- the crop type being treated and pedoclimatic conditions (soil, climate, plant species).

These factors interact to determine the final composition and effectiveness of the biostimulant product, and all must be considered in conjunction with product end users.

Impact of processing on biostimulant quality

The timing of harvest and environmental conditions play a significant role in determining the chemical composition and yield of bioactive compounds in seaweed extracts, thereby influencing product specifications, applications, and efficacy. Seaweed biomass typically contains high moisture levels (63%–96%), which can impact extraction efficiency, as well as stabilization and storage requirements, ultimately affecting product quality. Farmers need a product that can be used effectively and efficiently in conventional applicators. Processing variables, such as temperature, pressure, pH, and extraction methods, directly influence the physicochemical properties and bioactivity of the final product; inadequate specification of these parameters may lead to inconsistencies in efficacy (Baghel, 2023). Therefore, it is essential to consider the needs and expectations of farmers in order to guide targeted product development.

Lettuce field, Singer, CA, U.S. Photo by Lance Cheung, USDA, public domain.

3.4. Market development

Product relevance within agriculture

Currently, seaweed biostimulants are the second-largest segment of the global biostimulants market. The seaweed biostimulants segment was valued at over USD 1.4 billion in 2024, coming in just after the segment for amino acids and protein hydrolysates, valued at USD 1.5 billion in 2024. Seaweed extracts are particularly valued within the vegetables, fruit, and ornamental crops that have market pressures for quality and stress resilience (DunhamTrimmer, 2025).

For seaweed biostimulants to scale further and realize their full potential within the agricultural sector, several critical challenges must be addressed collaboratively by both aquaculture and agriculture stakeholders. Among these, determining appropriate price points and clarifying product expectations are paramount. Jointly establishing these criteria will allow terrestrial farmers to guide seaweed product development toward meeting their specific needs, while enabling the seaweed industry to better understand market demands and leverage economies of scale and innovation for producing high-quality products cost-effectively.

Furthermore, it is essential to comprehensively assess the benefits that seaweed biostimulants offer. Robust collaborative research should accurately measure the value delivered to diverse agricultural end users, encompassing both production efficiencies and wider environmental impacts, thereby reflecting true return on investment and informing realistic pricing strategies. Although it is ultimately important to show these benefits to all producers, it may be more practical to initially focus on regenerative and organic farmers and/or farmers who have market pressures to use organic fertilizers or fewer chemical fertilizers, as they are the most likely to adopt the use of seaweed biostimulants in the short term.

Market standards

Terrestrial farmers have increasingly high expectations for seaweed biostimulant products, demanding that they meet established agricultural standards while providing measurable benefits that complement existing farming practices. While established standards and guidelines for biostimulants exist in many regions globally, these frameworks have inconsistencies, which lead to regulatory confusion and often create unintended market access obstacles for seaweed biostimulants, primarily due to inadequate categorization and specification practices (Du Jardin, 2015). However, the trend is toward standardized regulatory frameworks and clearer product quality and safety criteria to enhance international trade and farmer confidence.

The European Union (EU) recently implemented the 2022 Fertilizing Products Regulation (EU, 2019), which established a uniform labeling framework for product packaging to indicate that harmonized EU requirements have been met, standardized requirements (including a comprehensive definition of "biostimulants"), and harmonized approval processes across all member states. These initiatives have aimed to protect farmers from unregulated products and facilitate access to solutions with verified credentials (Yuan, 2025). Comparable standards are needed globally, and collaboration between seaweed and land-based agricultural stakeholders is essential to advocate for a review of biostimulant regulations. Such efforts will foster industry development and aid stakeholders in navigating compliance requirements and market-entry strategies.

Market incentivization

Market incentives play a crucial role in establishing economic stability and resilience, especially for strategic product development. Governments can promote incentivization through various key mechanisms, such as subsidies, tax benefits, and regulatory reforms. Well-crafted incentives encourage private sector investment and help ensure that product development aligns with government policy goals.

Seaweed biostimulants align well with a range of international governance objectives, as detailed earlier in Sections 3.1 through 3.3 of this white paper:

- **Food security**: As part of an integrated crop management package, seaweed biostimulants can boost crop yields and quality while making plants more resistant to stress, thus maximizing output from existing farmland.

- **Enhanced agricultural sustainability**: Biostimulants have demonstrated their ability to improve soil health, increase water retention, and bolster crops' resistance to stress. These benefits may reduce reliance on synthetic fertilizers and pesticides, contributing to better environmental outcomes.
- **Supply chain and sovereign security**: Biostimulants offer farmers additional options to address modern agricultural challenges. Since many types of seaweed can be grown locally, transportation expenses and dependency on alternative international sources can be reduced.

It is essential that policy and legislation properly recognize and endorse seaweed biostimulants, as such endorsements will play a crucial role in advancing the sector's growth. Securing support from the agricultural community through effective advocacy is key to driving progress in this field.

Currently, seaweed biostimulants are typically priced higher than other soil amendments. To warrant this premium, agricultural producers require robust evidence demonstrating enhanced yields and other returns on investment associated with seaweed-based products, as previously described. Clearly articulating these advantages in the marketplace is essential for stimulating demand. A thorough understanding of market expectations will inform product development and strategic approaches to effectively address the price disparity over time.

Collaboration between seaweed and terrestrial farmers on R&D projects and field trials is essential to identify meaningful performance expectations and then scientifically validate product efficacy and modes of action. Demonstrating consistent performance across various crops, soil types, and climatic conditions will clarify economic advantages, including increased yields, enhanced crop quality, improved stress tolerance (such as resistance to drought or heat waves), and greater nutrient use efficiency. Customized products offer targeted value to terrestrial farmers and their suppliers but require clarity regarding product expectations and an understanding of their specific needs.

Research should also emphasize the broader environmental benefits, such as reduced reliance on synthetic fertilizers and improved soil health. Consumer and regulatory interest in sustainable, "residue-free" food products is increasing. As such, interest is increasing in natural and sustainable alternatives to existing fertilizer use. However, terrestrial farmers and

Agal Agal farmer Pasiagan, Bangoa Tawi Tawi, Philippines. Photo by Anthony Into,© TNC.

agronomists need to better understand these products and the optimal application methods, timing, and compatibility with other inputs. Providing explicit application guidelines ensures product efficacy and helps foster long-term customer relationships.

Finally, to build brand recognition, clearer communication is needed about the unique benefits of seaweed biostimulant products and how they stand out from not only other biostimulants but also other seaweed products. Achieving clarity calls for a focused communication strategy tailored to farmers, suppliers, and consumers. Collaboration among seaweed farmers, terrestrial farmers, and governments or investors will be essential for success.

Continuity and consistency of supply

At present, most products come from wild harvesting, which limits supply and puts pressure on natural populations; as a result, seaweed farming is viewed as a scalable and sustainable alternative for the future. The transition to aquaculture presents a significant opportunity to enhance both the availability and quality of species through the application of advanced farming techniques. Seaweed aquaculture can be conducted either in water or on land, each method presenting specific challenges and advantages.

The large-scale cultivation of farmed seaweed for the biostimulant sector faces several significant challenges, including cost control and ensuring consistent access to high-quality seedstock. Propagation and strain development demand specialized facilities and expertise, often requiring coordinated efforts among industry participants, research institutions, governmental bodies, and investors. Enhancing biostimulant production can be achieved either through stock improvement—which focuses on elevating plant quality—or through technological innovations aimed at increasing processing extraction efficiency. Greater product demand, economies of scale, and advancements in both breeding and extraction technologies are expected to contribute to cost reduction. Achieving these benefits will depend on effective collaboration among sector stakeholders, government agencies, and industry partners to drive the research and innovation necessary for implementing successful cost-reduction strategies.

Balancing production costs, product advantages, and pricing

Price is clearly a major factor influencing how widely seaweed biostimulants are adopted in agriculture. Seaweed biostimulants are generally positioned at the high end of the biostimulants market and considered premium products that can be used at relatively lower dosages. While it benefits terrestrial farmers to keep prices as low as possible, it is also important that pricing remains realistic to adequately cover production costs and reflect the full range of benefits these biostimulants can provide.

In the short term, aquaculture is unlikely to match the relatively lower price points of biostimulants made from wild-harvested seaweed due to the current higher operational costs for farming biomass versus harvesting wild. However, if seaweed biostimulants achieve the production benefits suggested by current research and also help cut reliance on synthetic fertilizers while improving soil health and water retention, the value to farmers could increase significantly. This greater value would justify co-investment by industry, government, and the private sector in advancing seaweed biostimulant development, with the aim of enhancing performance and achieving economies of scale, which in turn would hopefully lead to the price reductions needed for the sector's long-term success.

3.5. Summary and recommendations

In short, seaweed biostimulants present a significant opportunity for farmers on land. Seaweed products can improve crop performance and quality by boosting plant growth and increasing resistance to stress. They can help tackle emerging issues such as climate change, soil degradation, and water shortages by increasing plants' resilience to stress and improving soil health. However, for these benefits to be realized and further scaled, terrestrial farmers need clearer information about product performance across a range of crops, along with evidence proving their effectiveness under different farming conditions. Support from the land-based farming community to secure the resources for this R&D is crucial. As a result, possible partnership models need to be explored for co-investment in both research and infrastructure.

Opinions within the industry differ regarding who should take responsibility for driving market development for biostimulants. Some stakeholders advocate for collaboration between seaweed producers and land-based farmers to lobby for government support in areas such as developing the market, establishing product standards, and enhancing regulations. Others believe that this responsibility should fall solely on either the seaweed sector or governmental bodies. The primary focus may vary across jurisdictions. Nonetheless, it is evident that establishing reliable technical standards and scientific validation is crucial for increasing awareness and building trust among farmers. With this foundation, both producers and terrestrial farmers can effectively collaborate to grow the industry and unlock the full potential of seaweed biostimulants for sustainable agriculture.

R&D recommendations — Product development

Define product specifications: Land-based farmers should clearly articulate their product specifications and pricing expectations, enabling seaweed farmers to either demonstrate they meet these requirements or pursue enhancements to achieve the desired outcomes. Land-based and seaweed farmers should work together, with input and advice from governments, on research to determine agricultural requirements and assess the effectiveness of seaweed biostimulants, including meeting specific regional needs. Industry and government should sponsor investigations into how seaweed extracts influence plant physiology and improve stress resistance, and they should support studies that select strains with optimal biostimulant properties. Advancing this knowledge will lead to better application strategies and higher-quality products.

Organize field trials and data gathering: Coordinate long-term field trials covering a range of crops and environments to produce robust data on yield improvement, nutrient uptake, and resilience to stress. Support trials that establish best practices for consistent application methods across various crop types and seaweed species. Facilitate meta-analyses to critically evaluate global research, identify the most effective production and application strategies, and strengthen the overall body of evidence for biostimulants. This evidence base is essential for supporting farmer adoption and meeting regulatory requirements.

Support the discovery of new compounds and traits: Examine both common and lesser-known native seaweed species to uncover novel biostimulant or beneficial compounds and traits, helping diversify product offerings and open up new revenue opportunities.

Improve processing methods: Invest in research to advance efficient, cost-effective postharvest processing technologies that ensure high-quality extracts and minimize waste.

R&D recommendations — Knowledge sharing

Promote industry collaboration: Strengthen support for industry associations to enhance collaboration among researchers, stakeholders, producers, and government bodies. Identify key academic partners and make sure that R&D aligns with market needs. Develop online platforms that can increase access to available information and data.

Advocacy and government engagement recommendations

Simplify permitting processes: Push for a more straightforward permitting system (for seaweed farm development, as well as product specifications, application, and market access) to reduce costs, administrative workload, and unnecessary delays across government departments.

Establish product standards and traceability: Advocate for the creation of standardized testing methods and certification programs for seaweed biostimulants to build product trust and enable entry into premium markets.

Provide financial incentives: Extend grants, subsidies, or tax benefits to farmers implementing seaweed-based solutions and enterprises developing biostimulant technologies. Recommend integrating


Training on Rote Island, Indonesia, © TNC.

seaweed biostimulant products into national environmental credit systems, such as carbon or biodiversity credits, to encourage sustainable practices.

4. Government and investors — What is the opportunity in seaweed biostimulants?

4.1. Overview of government and investor opportunities

With an increasing emphasis on sustainable farming practices worldwide, governments are actively promoting strategies to improve food security, support sustainable agriculture, address climate issues, and stimulate local industries and markets. Seaweed biostimulants can address a number of significant sustainability concerns inherent in traditional food supply systems but, importantly, can also offer notable improvements in terrestrial crop performance.

The agricultural sector is increasingly embracing sustainable and innovative practices to enhance crop productivity and quality. Seaweed biostimulants offer considerable advantages across a diverse range of crop types, promoting higher yields and improved quality while mitigating stress through enhanced soil health and improved resilience to environmental stressors.

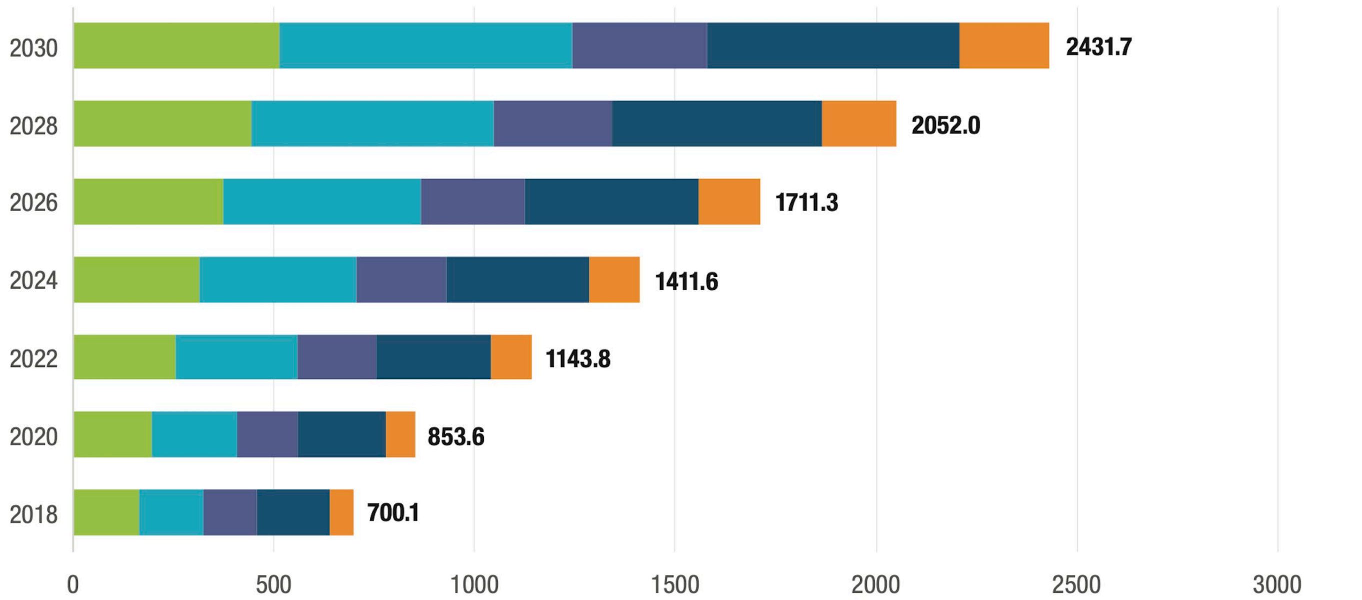
Seaweed extracts, particularly agricultural biostimulants, represent a rapidly expanding global market (World Bank, 2023). In 2024, the value of the global seaweed extracts market exceeded USD 1.4 billion (Figure 5), with forecasts indicating that growth in this sector will remain strong and estimates suggesting between 8.6% and 10.9% compound annual growth rate (CAGR) over the next 5 years (DunhamTrimmer, 2025).

Seaweed extracts are anticipated to maintain their status as a strong and distinctive segment within the biostimulants sector, driven by opportunities in quality improvement and advanced stress management in a range of premium crops. Although global expansion is expected to continue, growth projections for Latin America and Southeast Asia are particularly promising, reflecting concurrent developments in horticultural markets within these regions (DunhamTrimmer, 2025).

Several companies have recognized the potential of this global biostimulants market and have already established strong positions, including Acadian Plant Health in Canada, Kelp Blue with operations in Europe and Africa, and Ficosterra in Spain. Additionally, organizations such as Aquagri in India and Leili Agricultural Company in China have transitioned from traditional seaweed sectors to capitalize on opportunities within the biostimulants industry. While Europe and North America currently serve as key centers for production and market activity, significant opportunities exist on a global scale. Consequently, government support for the seaweed biostimulants sector presents significant opportunities to foster economic and environmental benefits, while reinforcing national food security.

Figure 5. Estimated value (USD) of seaweed extracts across Canada and the U.S., Latin America, Europe, the Asia-Pacific region, and Africa year on year from 2018 to 2030 (DunhamTrimmer, 2025).

GLOBAL SEAWEED EXTRACTS: REGIONAL VALUES (MN) USD 2018-2030



REGION	2018	2020	2022	2024	2026	2028	2030
US/Canada	164.1	196.2	255.8	313.6	374.8	442.2	514.6
LATAM	160.9	212.0	303.6	391.2	491.4	604.7	728.8
Europe	132.5	152.0	194.6	225.2	258.2	295.0	335.4
Asia/Pacific	180.6	217.3	287.7	355.8	434.0	525.3	630.3
Africa	62.0	76.2	102.1	125.9	152.8	184.9	222.6
TOTAL	700.1	853.6	1143.8	1411.6	1711.3	2052.0	2431.7

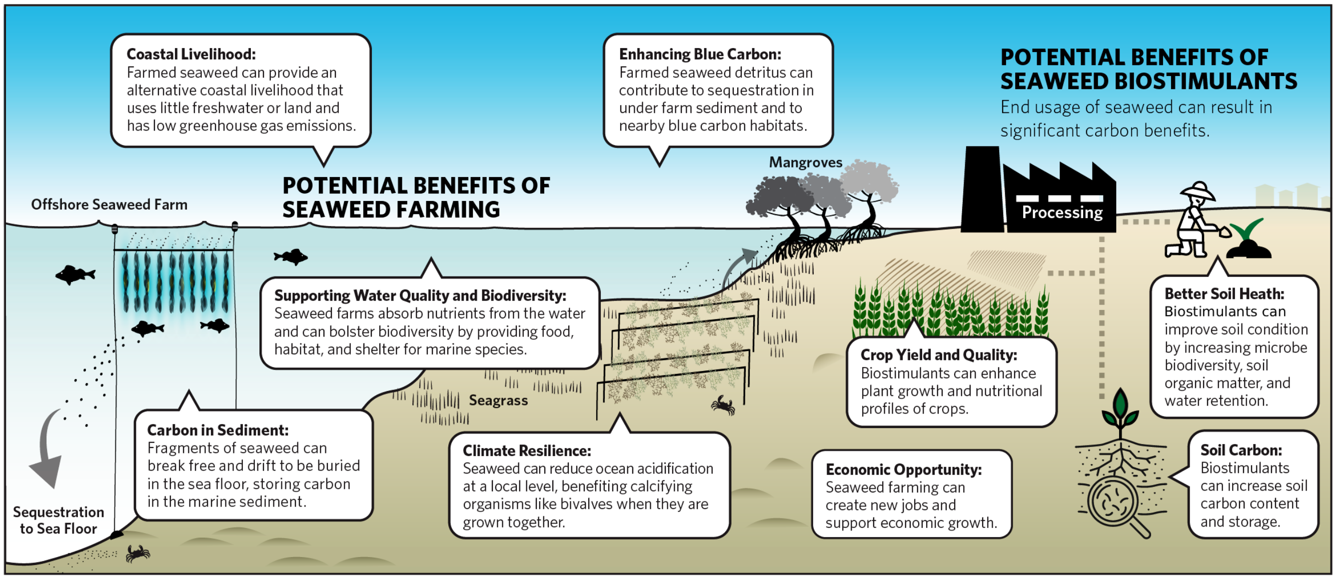
Strengthening food security and resilience

Food security requires more than food production; it also means guaranteeing that everyone has access to affordable and nutritious options and that food production systems are based on sustainable practices. Land-based farmers have been striving to produce food in more sustainable ways for a long time. However, climate change, geopolitical issues, and input costs are challenging food systems and traditional production methods globally (Daszkiewicz, 2022). Land-based farmers are also facing a crisis of fertility; according to the latest *The State of Food and Agriculture* report from the Food and Agriculture Organization of the United Nations (FAO), approximately 1.7 billion people live in areas where human-induced land degradation—including soil erosion and nutrient depletion—is actively causing crop yields to fall (FAO, 2025).

As these challenges strain food systems, farmers are seeking innovative approaches to improve their methods, restore soil health, and boost profitability. Seaweed biostimulants can help address a range of critical issues facing global agriculture (Figure 6), including:

- enhancing crop yields and quality by 5% to over 200%, depending on factors like crop type and environment;
- promoting stronger root systems, boosting soil carbon, improving structure, and increasing water efficiency;

Figure 6. Potential benefits of seaweed farming and seaweed biostimulants for coastal livelihoods, marine ecosystems, and plant and soil health. © TNC.



- improving soil health by enhancing aeration, drainage, organic matter content, and nutrient uptake; and
- supporting broader sustainability efforts by reducing dependence on synthetic agrochemicals and lowering environmental impacts.

Benefits to terrestrial agriculture are discussed in further detail in Section 3.2, "Applications in Agriculture." With collaboration and strategic planning, as covered here in Section 4, farmers can use seaweed biostimulants as essential tools.

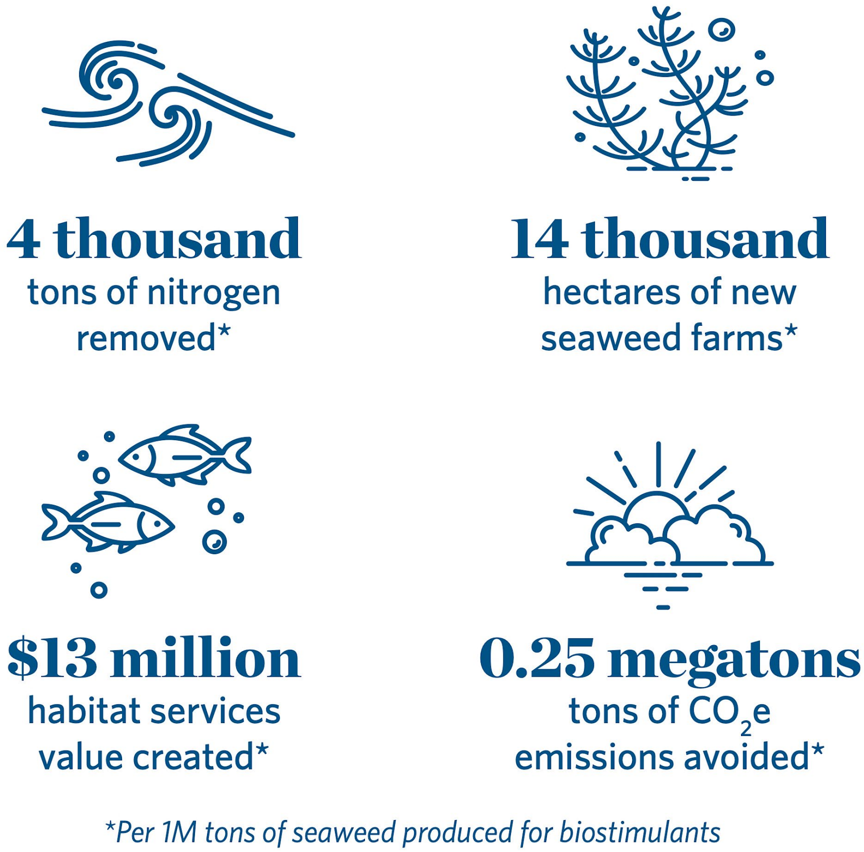
Environmental and climate benefits

Biostimulants can be used in both organic and conventional farming, supporting a movement toward more natural and sustainable agricultural methods that align with consumer expectations while addressing the overall reduction in productivity increasingly observed as a result of climate-related stressors (DunhamTrimmer, 2025). Biostimulants not only aid in better nutrient management but also strengthen the resilience of global food systems. As unpredictable climate events increase and secure nutrient supplies become crucial, biostimulants are becoming essential to help crops withstand stresses like drought and extreme heat. Field studies have reported significant yield improvements for various crops, even as environmental conditions become more challenging (Khan et al., 2009; Nanda et al., 2022).

Seaweed cultivation stands out for its efficiency—when farmed well, it does not require land, fresh water, pesticides, or fertilizers (TNC, 2021). Although recent research indicates that seaweed farming may result in relatively small amounts of carbon sequestration (Duarte et al., 2025; TNC & Bain & Company, 2023), numerous other environmental and production advantages exist, particularly with seaweed grown for biostimulant use, that help counteract climate change (Figure 7). Life cycle analyses show that seaweed-based biostimulants offer valuable low-emission options for achieving global net-zero targets (Thomas et al., 2024). Additionally, an increasing body of work shows that cultivating seaweed improves marine ecosystems not only by absorbing excess nutrients but also by mitigating local ocean acidification during growth and providing habitats for marine life (Gentry et al., 2020). By replacing carbon-intensive products and decreasing reliance on chemical fertilizers, seaweed biostimulants can reduce agricultural emissions, generating roughly 50% less CO_2 per application compared to synthetic fertilizers (TNC & Bain & Company, 2023). All of these benefits contribute to advancing climate-smart sustainability initiatives.

Achieving growth targets in the biostimulants industry will require a combination of wild harvesting and aquaculture. While seaweed biostimulants hold potential worldwide, factors such as suitable species, environmental conditions, and regulations differ greatly between regions. For sustainable progress, the aquaculture sector will need to evaluate local species and circumstances, weighing their opportunities and challenges, and establish cultivation standards and governance systems that appropriately address the related risks.

Figure 7. Indirect sustainability benefits associated with every million tons of seaweed production for biostimulants (TNC & Bain and Company, 2023).



The Aquaculture and Marine Stewardship Councils (ASC-MSC) have developed a global seaweed standard for sustainable seaweed harvesting and farming that includes both wild-harvest criteria and aquaculture guidelines. It can help ensure the ecological integrity, traceability, and social license of this emerging industry (ASC-MSC, 2017). The standard is presently undergoing revision to maintain its relevance within the evolving industry, incorporate widely accepted best practices, and address sustainability requirements. This review presents an opportune moment to contribute explicitly to the process and expressly outline standards and expectations for biostimulant-specific seaweed production.

Government responsibility for social acceptability

Currently, seaweed aquaculture enjoys positive community perception, but maintaining this support depends on adopting strong sustainability standards. To secure social license, the sector must foster community trust by achieving legitimacy, credibility, and reliability—accomplished through adhering to regulations and sustainability expectations, acting with integrity, being transparent, and cultivating relationships based on shared values and responsible practices. This process includes listening to public concerns, demonstrating care for the environment, and maintaining open dialogue.

Collaboration between industry and regulators is essential to ensure both on-water and on-land practices are guided by thorough risk assessments and robust management strategies that prioritize environmental safety, transparency, and active community participation. Operators should openly share their farming methods, be candid about their actions, and communicate proactively, especially when addressing difficult issues. Seaweed farming for biostimulants has a clear advantage in relation to social acceptability, as its value proposition not only seeks to deliver environmental benefits on water, such as safeguarding waterways and biodiversity, but also aims to support improved results for land-based agriculture.

4.2. Opportunities for government/investor involvement

Market drivers — Shaping the growth of the biostimulants industry

Meeting the expected growth in the seaweed biostimulants market (DunhamTrimmer, 2025; World Bank, 2023) will require a significant boost in seaweed production, opening market opportunities for both new and existing seaweed-farming regions. While rising fertilizer prices may be encouraging farmers to consider seaweed biostimulants, cost competitiveness remains a challenge due to higher overheads in seaweed aquaculture. Achieving price parity may require differentiating seaweed as a premium product or reducing production costs through improved efficiency, incentives, or subsidies.

Seaweed biostimulants were originally mainly used in organic and high-value crops; however, conventional agriculture is now adopting them much more widely to serve both economic and sustainability needs. This growing interest has seen the need for new, targeted products to address specific agronomic challenges, including the reduction in overall productivity associated with climate change, and to appeal to environmentally aware consumers (DunhamTrimmer, 2025). As biostimulant use spreads worldwide, producers and distributors are expanding networks to access new markets. Consequently, creating a competitive environment with fewer entry barriers will be critical.

To enhance adoption, seaweed biostimulants must demonstrate reliable efficacy and deliver measurable returns on investment. Some farmers remain skeptical due to variable field outcomes and a lack of extensive large-scale trials. Many seaweed biostimulant companies are relatively small, making it challenging for them to compete with well-established synthetic fertilizer and biostimulant suppliers that possess much greater R&D resources. Nevertheless, the growing body of robust scientific evidence supporting these products helps distinguish them from synthetic competitors and contributes to favorable profit margins.

Government needs to work with industry (seaweed and land-based farmers) to promote seaweed biostimulant products, validate and communicate their effectiveness in real-world settings, streamline supply chain operations, and position seaweed as a viable global alternative to synthetic products.

The value proposition of seaweed biostimulants is becoming increasingly evident, and as such, strategic collaboration among stakeholders and government support will be vital to help ensure these products meet their full potential.

Regional market differentiation

In 2022, Europe represented about half of the worldwide biostimulant market, valued between USD 1.5 billion and USD 2 billion, with a CAGR of 10%–12% (DunhamTrimmer, 2025). Projections for 2025 indicate that Europe will remain the largest player in the global biostimulant sector, although its share may decline to approximately 34% of the overall (DunhamTrimmer, 2025). This change does not point to reduced activity in Europe, but rather to increased production in other regions. The Latin American market, led by Brazil, is experiencing rapid expansion. The Asia-Pacific region also maintains a sizable and active market, particularly in countries like China, where sustainability is becoming more important (DunhamTrimmer, 2025; FAO, 2025; World Bank, 2023). By 2024, the Middle East and Africa accounted for around 2% of global revenue, but these areas are expected to see notable growth—an estimated CAGR of 12% from 2024 through 2031 signals substantial progress ahead. The U.S. and Canada also play a key role, especially in farmed kelp production, where they have emerged as leaders (DunhamTrimmer, 2025; FAO, 2025; World Bank, 2023).

While direct gross domestic product (GDP) contributions by region are difficult to find, available market share and revenue data give insight into the industry's economic impact across different areas (see Table 5). Asia—specifically China, Indonesia, South Korea, Japan, and the Philippines—has long been the center of the seaweed industry, driven by culinary traditions and extensive aquaculture. The region's production focuses mainly on human consumption and the carrageenan market. North America and Europe are growing quickly, albeit from smaller starting points, spurred by increasing demand for sustainable

Table 5. Regional market shares for the seaweed industry and seaweed biostimulants specifically, with key features noted.

Region	Seaweed industry market share (revenue/production)	Seaweed biostimulants (market position/growth)
Asia	Dominates globally, with over 97% of production and 63%–77% of market share.	Largest market share due to established agriculture and government initiatives.
Oceania	Has a minor global share (approx. 0.05%), with most coming from cultured seaweed (e.g., in Australia).	Growing market, driven by potential for methane-reducing feed supplements.
Europe	Has a small global production share (approx. 0.8%) but the fastest-growing market by value.	Significant demand for natural and organic agricultural inputs; high growth rate.
North America	Accounts for a small share (approx. 1.36%), mostly from wild harvest.	Emerging market with increasing interest in sustainable agriculture solutions.
Latin America	Is not a major farming region (Chile is the top wild harvester) but has a long history of use.	High-growth region with expanding agricultural infrastructure and strong government support.
Africa/ Middle East	Has a small share (approx. 0.41%), with Tanzania as a primary producer.	This region is the fastest-growing regional market for commercial seaweed products.

and natural goods, such as plant-based foods, cosmetics, and agricultural biostimulants. Developing the seaweed biostimulants sector brings new prospects for seaweed producers and offers substantial advantages for regional economies as a whole.

Focused government support for seaweed farming programs has produced strong results in many countries. Increased government investment can help establish robust domestic supply chains, lessen reliance on imports, make better use of local resources, and support existing processing facilities. Government support in China and South Korea has led to decades of substantial growth, and various African nations—including Tanzania, a founding member of the UN Global Seaweed Initiative—understand the value in developing their domestic seaweed sectors. Tanzania's efforts emphasize boosting farmers' earnings, improving practices, adding value through processing, and empowering local communities, with women playing prominent roles. Recently, an Australian government grant helped fund a hatchery network for *Asparagopsis* cultivation, with projected benefits suggesting a benefit-cost ratio of 8.4, well above expectations (GHD, 2025).

The key differences in the global seaweed biostimulant markets would seem to lie primarily in the maturity of the market, the primary product application, and the specific drivers in each region (Table 6). In essence, Europe and the U.S. are focused on efficiency, sophisticated applications that include biostimulants, and regulatory compliance. Asia is the powerhouse of production, with a stronger focus originally on food and carrageenan but now evolving toward higher-value products. The regions where biostimulants are emerging as significant markets are using local demand for effective market development, alongside industry and government sustainability expectations, to develop climate-specific solutions for product differentiation.

The variations in maturity, application, and sustainability drivers across regional markets (Table 6) clearly show that aligning the seaweed biostimulant industry with regional agricultural goals can create demand that supports and incentivizes development. Furthermore, governments should play a key role in aligning the industry and regional goals. A good example is Greece's incentivization of biostimulants within its common agricultural policy (CAP) strategic plan. Seaweed biostimulants could help

Table 6. Comparison of regional market differences in overall seaweed production.

Attribute	Europe & U.S. (mature markets)	Asia (largest producer)	Latin America, Africa, Middle East, & Oceania (emerging markets)
Market maturity	**High**: Established regulations, sophisticated product lines, and high adoption rates.	**High volume, evolving value:** Dominates raw material production. Shifting toward value-added extracts and modern applications.	**Emerging**: Smaller markets with high growth potential, often focused on specific local opportunities or niche innovation.
Agricultural application	**Diverse & widespread:** From high-value horticulture to large-scale row crops. Applications are sophisticated and scientifically optimized.	**Traditional & modern**: Applications range from direct use to modern treatments across various crops.	**Targeted & niche**: Often used to diversify local production, improve specific regional crops, or support innovative applications like methane reduction.
Sustainability drivers	**Regulatory & consumer demand**: Driven by the need to reduce reliance on synthetic chemicals and meet consumer demand for sustainable products.	**Utilization & waste reduction**: Focused on utilizing existing aquaculture streams and converting processing waste into useful products.	**Economic & climate resilience**: Focused on building local economies, providing climate-resilient farming solutions, and achieving specific climate goals like methane reduction.

fulfill CAP objectives on stable food supplies, equitable incomes, and sustainable farming across Europe and align well with the EU's Farm to Fork Strategy, which aims to reduce nutrient losses by 50% by 2030 without harming soil fertility (EBIC, n.d.). Similarly, seaweed biostimulants could support a range of national and international policies on sustainability, food security, and trade while helping reduce carbon footprints through local sourcing.

4.3. How can the government contribute?

As demonstrated in Sections 4.1 and 4.2, seaweed biostimulants offer considerable economic opportunities and hold significant promise for supporting environmental sustainability. These attributes make them valuable assets in addressing issues related to food security and climate change. To fully realize these advantages and foster the growth of the global market, it is essential for both government and industry to adopt a coordinated approach to planning and regulation.

Supportive regulation

Governments committed to aquaculture need to ensure sustainable ecosystem-based management. The regulatory frameworks for seaweed aquaculture worldwide are many and varied. Unfortunately, regulatory complexity hinders both production and market access. To support the seaweed sector as it grows, the industry needs a robust, clear, and flexible management framework, which can foster confidence for investment and innovation. It is also vital to regularly review policies to maintain alignment with industry needs and support continued development. A global review of regulatory best practices may help address these challenges.

Start-up support

Securing permits for establishing aquaculture zones can be a complex process, requiring navigation through multiple regulatory frameworks at both local and national levels. Providing support for site selection not only accelerates industry development but also ensures environmental sustainability. Comprehensive planning and transparent environmental monitoring are essential for building investor and community trust. Governments can further facilitate sector growth by identifying aquaculture development areas and covering baseline costs.

Key areas for government support

Incentives:

- Implementing expedited processes to open aquaculture development areas for seaweed cultivation.
- Making direct government investments in environmental impact assessments and baseline data collection to underpin the establishment of the seaweed aquaculture industry.
- Enhancing mechanisms that attract investment in the sector.
- Supporting workforce training and technical skills development, with emphasis on remote regions and Indigenous communities.
- Encouraging cross-jurisdictional information sharing, particularly concerning risk identification and management strategies.

Regulations:

- Streamlining administrative requirements for aquaculture start-ups by simplifying application procedures; improving access to pre-approved development areas or zones; facilitating the exchange of scientific data and research; and reducing initial establishment costs, such as rents and fees, especially during pilot or research phases.
- Increasing clarity and understanding of planning and approval processes within relevant government agencies to minimize delays.
- Standardizing procedures and clearly outlining approval pathways in each jurisdiction to assist proponents in selecting the most appropriate options for their development goals.

Market access/development support

Many countries and regions lack harmonized legislation for biostimulants, often categorizing these products ambiguously between fertilizers and plant protection agents. These inconsistencies result in a confusing mix of national laws and definitions, which in turn creates uncertainty for manufacturers, hampers cross-border trade, and slows innovation. Such regulatory barriers tend to benefit larger companies with greater resources to manage legal complexities, potentially leading to increased market consolidation. Both regulatory barriers and market consolidation make it harder for smaller, innovative businesses to compete.

To address these issues, governments should streamline and expedite the permit application process for sustainable seaweed aquaculture, coordinating efforts among various agencies to offer a clear and unified development path. Notably, within the last decade, Europe has replaced 27 separate national approval processes with a single EU-wide system for plant biostimulants (EU, 2019), creating greater consistency across member states, reducing administrative burdens and costs, and encouraging swifter market access and innovation. Other regions could establish similar clear standards and expectations to support product credibility and market entry. Collaboration among industry leaders, researchers, and regulators is essential to ensure that policymaking is coordinated, coherent, and informed by diverse perspectives.

Additionally, governments can foster the creation and adoption of reasonable standards and certifications to boost both credibility and acceptance of these products, enabling producers to reach premium and organic markets. The absence of standard testing protocols and consistent data requirements for proving product efficacy and safety also stifles R&D, making it challenging to demonstrate value to both regulators and farmers. By implementing integrated policy and R&D recommendations, governments can create an enabling environment that supports the growth of the seaweed biostimulant sector, resulting in substantial economic, social, and environmental benefits.

R&D — Supporting innovation

R&D funding plays a pivotal role in driving innovation within cultivation techniques, processing technologies, and product applications. Strategic investment in these areas enables the pursuit of patenting and licensing opportunities, as well as the commercialization of novel technologies. Ongoing support for research, development, and innovation enhances prospects for licensing and technology transfer. Additionally, government participation can further promote advancements across cultivation methodologies, processing strategies, and new product applications.

R&D — Capacity-building, capability-building, and education

In many countries outside Asia, seaweed farming is still developing and needs significant government support to build technical expertise in cultivation and product innovation. Investment in education and training ensures a skilled workforce for industry growth.

Nursery cultivation is an essential underpinning to industry success, but it requires advanced knowledge and specialized facilities for quality seedstock. Government funding can drive research to improve breeding methods and seedstock quality, with national hatcheries lowering barriers for new producers and advancing the sector. Since this research benefits the entire industry, public funding is often necessary at the early stages. Such investment also supports year-round jobs and strengthens coastal communities.

Standardizing best practices, validating products scientifically, and ensuring reliable seedstock supply can benefit from centralized or government-supported approaches. Targeted investment can help optimize cultivation methods for regional development and boost or fast-track economic growth. In areas where the investment base is low or the sector is just starting, the development of a nursery network can provide critical start-up support, a basis for disease-free seedstock, and both technical and biosecurity knowledge sharing to support industry expansion and the development and introduction of new species.

Knowledge exchange is crucial in the early industry phases. Government involvement fosters collaboration among researchers, stakeholders, and agencies. Existing programs support capacity-building and synergy between aquaculture and agriculture. For example, the EU Agricultural Knowledge and Innovation Systems initiative advances sustainable agriculture by promoting innovation and supporting the adoption of biostimulants and organic fertilizers. Organizations like FAO and the World Bank further facilitate knowledge transfer and align development efforts with market needs to drive industry progress.

Product validation and optimization

Government or strategic independent R&D investments in field trials that gather evidential data are essential for farmer adoption and regulatory approval. Therefore, support for large-scale, multi-year trials across various crops and conditions is needed to provide solid data on yield increases, nutrient efficiency, and stress resilience. Although many farmers want this information, they are often reluctant to risk their cash crops; thus, some form of government insurance or underwriting could encourage greater collaboration in R&D efforts.


Aquaculture in Kenya. Photo by Hannah Packman, © TNC.

Additionally, governments can focus on research and the advancement of technologies to better understand how seaweed extracts influence plant physiological processes and stress tolerance. This scientific insight informs strategies for optimal application and superior product development. While such research is not strictly necessary to prove agricultural production benefits, it does aid future product refinement and applications tailored to country-specific needs, like drought or flood scenarios.

Processing support and innovation for economic optimization

Processing plays a crucial role in the supply chain and greatly influences both product quality and application. In fully integrated businesses, processing might serve as the final stage of product development, while in traditional, linear supply chains, it may function as a key independent partner. Seaweed farmers often perform basic primary processing steps—such as drying or extracting alginate solutions—to stabilize products. However, when secondary processing or further product differentiation occurs elsewhere, particularly offshore, the largest economic gains are often realized outside the local region.

Government co-investment in developing advanced postharvest processing technologies and establishing modern, cost-effective facilities can significantly support industry growth by producing high-quality extracts and minimizing waste. This support may come through direct funding or by implementing policies and financial incentives that attract third-party investments. With proper management, these actions can help retain more profits and economic benefits locally, boost primary production through stronger market demand, foster skill and capability development in regional areas, and encourage product innovation.

Government participation can also bridge the gap between seaweed producers and agricultural farmers, aligning production capacity with market needs and ambitions, thereby accelerating the pace of innovation. In addition, a review of product potential from particular input materials could be a useful underpinning for broader market development and investment.

R&D — Market development

Government-sponsored initiatives focused on certification, accreditation, and traceability can increase product value and enhance market acceptance, enabling producers to access premium markets and capitalize on sustainability advantages. Social studies that identify consumer preferences and possible obstacles to entering the market will play a key role in supporting and directing these efforts. Collectively, this approach can facilitate international recognition of the industry's potential and facilitate the unlocking of global value chains and broader market opportunities.

Governments may provide incentives, subsidies, or grant programs to land-based farmers who adopt sustainable seaweed-based biostimulants. These measures can help offset the cost differential between innovative seaweed products and traditional lower-cost alternatives, thereby encouraging demand and supporting ongoing market viability.

Many countries currently rely on substantial imports of seaweed products to augment domestic supply or to provide feedstock that is locally unavailable. Strategic investments can reduce this dependency by strengthening domestic supply chains, identifying and utilizing local resources, and decreasing reliance on international markets.

4.4. Role of private investors

Independent investors play a pivotal role in supplying venture capital and, as such, could advance the seaweed biostimulant sector by investing in start-up innovation, enhancing technology, strengthening local supply chains, scaling production, and addressing market complexities that may not be fully addressed by larger corporations or public funding sources.

Private investors often target areas in building capacity and markets. Angel investors focus on critical seed and early-stage capital for start-ups, which, in the case of biostimulants, could foster advancements in new species identification, culture techniques, extraction methods, product formulations, and even product delivery systems. They could support pre-commercial trials and pilot programs to generate valuable data on product efficacy and environmental benefits. This enhanced understanding could help reduce risks and attract subsequent institutional investment.

Impact investors particularly target ventures that deliver both financial returns and progress toward environmental and social objectives, including climate change mitigation, biodiversity conservation, and support for coastal communities. They tend to have a longer-term perspective, supporting start-ups through early-stage market uncertainties, regulatory hurdles, and scaling obstacles. Investments made with a gender perspective that promote livelihood opportunities for women, who are often key contributors in coastal economies, may be particularly attractive. Impact investors may also look to facilitate the establishment and expansion of sustainable seaweed farming operations in coastal and rural areas, generating employment and economic development. For example, companies such as Mawimbi Ocean Innovations in Kenya employ a "seaweed as a service" model to create farming opportunities within coastal regions (Mawimbi Ocean Innovations, n.d.; Msuya et al., 2022).

Funding enterprises focused specifically on technology advancement, product development, and biorefinery approaches could identify new bioactives and extraction technologies to support multiple high-value products from seaweed biomass, improving the financial sustainability of the entire supply chain. Investments in local universities and research institutions can accelerate technological and capability advancement tailored to regional species and environments.

The risk (in)tolerance and mission-driven focus of independent investors make them very valuable partners in progressing the seaweed biostimulant industry. Their support fuels the innovation and scaling required for this promising and sustainable sector and sends a very clear message to the broader market that the sector has legs.

The connection between public and private investment is complex and can be either complementary or competitive, depending on factors like economic conditions, the type of investment, and funding sources. Complementary funding happens when public investment encourages private investment by raising productivity, creating opportunities, and increasing economic demand. Alternatively, public investment can reduce private investment by increasing government borrowing, which can raise interest rates and make it more expensive for private firms to borrow money and invest.

4.5. Summary and recommendations

The seaweed biostimulant industry offers substantial prospects for expansion. Each stakeholder within the seaweed production value chain can play a vital role in promoting the sustainable growth of this sector. Effective collaboration throughout the supply chain will enhance unity, operational efficiency, market stability, risk mitigation, and innovation.

Governmental involvement is instrumental in advancing the market by developing transparent, efficient regulatory frameworks and implementing targeted financial incentives. The government should prioritize funding for research initiatives focused on promoting biostimulant product innovation and trialing, advancing processing technologies, optimizing cultivation practices, and providing essential infrastructure such as biorefineries for multiproduct extraction. Defining best practices and product standards for governance and market entry, alongside realistic risk assessments to guide environmental and business oversight, is also imperative.

Recommendations for policy development

Streamline permitting for aquaculture: Establish a unified online platform or agency to manage all permitting processes related to the creation and operation of seaweed farms. A one-stop-shop model could reduce administrative burdens, costs, and delays associated with navigating various governmental departments.

Develop product standards and traceability: Encourage the development of standardized testing protocols and certification schemes for seaweed biostimulants. These measures enhance product credibility and facilitate access to premium and organic markets.

Provide financial incentives: Implement grants, subsidies, or tax credits for farmers adopting seaweed-based solutions and companies innovating biostimulant technologies. Exemplary programs, such as the recent USDA Partnership for Climate-Smart Commodities, may serve as effective models.

Recognize environmental credits: Officially include seaweed aquaculture and biostimulant products in national environmental credit programs (e.g., carbon credits, nutrient remediation, biodiversity credits). This may provide supplementary revenue opportunities for farmers and could help incentivize the use of biostimulants via improved sustainability practices.

R&D recommendations — Supporting production and product development

Support cultivation optimization: Support R&D for cost-effective, high-efficiency farming methods tailored to regional needs, including both land-based and offshore systems. Research should focus on strain selection that promotes desirable biostimulant characteristics.

Establish national nursery networks / R&D support: Invest in establishing public or private nursery networks to ensure a consistent supply of high-quality, disease-free seedstock and relevant knowledge transfer for start-ups. This investment may translate into support for industry development more broadly (e.g., biosecurity, product development, and market development) as the industry scales up.

Support the development of postharvest processing technologies: Fund R&D for modern, economical processing facilities to produce high-quality extracts while minimizing waste.

R&D recommendations — Market access

Support product efficacy validation: Facilitate large-scale, multi-year field trials encompassing various crop types, environments, and organic and regenerative farmers to generate robust data addressing key agricultural outcomes, such as yield improvement, nutrient efficiency, and stress tolerance. Evaluate agronomic effectiveness, soil health benefits, and possible drawbacks like heavy-metal buildup. Additionally, consider implementing farmer insurance schemes linked to trial participation to enhance engagement. The resulting evidence base will support both grower adoption and regulatory approvals.

Promote bioactivity and traits innovation: Promote research initiatives to clarify the modes of action through which seaweed traits and extracts influence plant physiological processes, enhance resilience to stress, and optimize strain selection. Advancing this knowledge will accelerate the realization of benefits, inform effective application strategies, elevate product quality, and drive improved sustainability results. Support the investigation of native and underutilized seaweed species to identify novel compounds and traits with biostimulant or other beneficial properties, fostering market diversification and creating additional revenue opportunities.

Demonstrate sustainability and Sustainable Development Goal (SDG) advantages: Facilitate comprehensive cradle-to-grave life cycle assessments (LCAs) to monitor environmental impacts from cultivation through end use. Take into account broader ecological benefits—including in-water biodiversity and ocean acidification effects—typically not addressed by conventional LCA methodologies. Promote the development of innovative, standardized protocols and consistent reporting practices to enhance performance comparability across regions, production methods, and traditional farming approaches that do not incorporate biostimulants.

R&D recommendations — Knowledge sharing and capacity development

Foster industry collaboration: Support and sustain online platforms and industry associations to promote coordination among researchers, industry stakeholders, producers, and government agencies, aligning R&D activities with market demands. Bearing in mind the limitations arising from intellectual property and legal confidentiality concerns.

Develop the workforce: Invest in comprehensive education and training to cultivate expertise in seaweed aquaculture, biotechnology, and processing, ensuring a skilled workforce capable of sustaining future industry growth.

By implementing these integrated policy and R&D recommendations, governments can create a sup-

Mulutseribu Seaweed Farms, Indonesia.
Photo by Kevin Arnold, © TNC.

portive environment that enables the seaweed biostimulant industry to thrive, delivering significant economic, social, and environmental benefits.

Collectively, these recommendations can foster a supportive environment for the seaweed biostimulant industry's expansion, generating meaningful economic, social, and environmental benefits.

R&D recommendations — Sustainability and community engagement

Foster social acceptability: Currently, seaweed aquaculture enjoys positive community perception, but maintaining this support depends on adopting strong sustainability standards. To secure social license, the sector must foster community trust by achieving legitimacy, credibility, and reliability—accomplished through adhering to regulations and sustainability expectations, acting with integrity, being transparent, and cultivating relationships based on shared values and responsible practices. This process includes listening to public concerns, demonstrating care for the environment, and maintaining open dialogue.

Collaboration between industry and regulators is essential to ensure both on-water and on-land practices are guided by thorough risk assessments and robust management strategies that prioritize environmental safety, transparency, and active community participation. Seaweed farming for biostimulants has a clear advantage in relation to social acceptability, as its value proposition not only seeks to deliver environmental benefits on water, such as safeguarding waterways and biodiversity, but also aims to support improved results for land-based agriculture.

5. Key research needs

The review and recommendations covered in this white paper highlight several key knowledge gaps in the development and scaling of the seaweed biostimulant industry. These gaps can also be thought of as opportunities for farmers, government entities, investors, and other stakeholders to advance this promising field:

Optimized cultivation techniques: Region-specific, cost-effective, and efficient cultivation methods are needed, including both terrestrial and offshore systems. Further research could help identify optimal strains with strong biostimulant properties that cater to these needs.

Seedstock supply and nursery networks: Some species are well-established with strong seedstock supply chains. Still, in many countries and for some developing species, there are gaps in the consistent supply of high-quality, disease-free seedstock. These countries and species would benefit from the establishment of robust national nursery networks to facilitate a reliable seedstock supply for start-ups.

Postharvest processing: Advanced, economical postharvest processing technologies are generally underdeveloped. Further research would be beneficial to improve extract quality, align by-products with end-user needs, and reduce waste.

Product efficacy and field data: Comprehensive field trials and data collection across diverse crops and environments are lacking in many geographies. Additional research should occur on yield improvements, nutrient uptake, stress benefits, and the extent to which traditional fertilizer use may be offset or adjusted across different crops and scales to support farmer adoption and regulatory approval.

Bioactivity mechanisms: The specific physiological mechanisms by which seaweed biostimulants enhance plant growth and stress resistance are not fully understood. Further research on and understanding of the underlying modes of action of seaweed biostimulants could yield optimized application protocols and product development.

Discovery of novel compounds and traits: Native and underutilized seaweed species remain underexplored for potential new biostimulants or beneficial traits and compounds. Expanding the research and use of novel compounds and traits could expand market diversification and revenue opportunities.

Knowledge sharing and industry collaboration: There are gaps in coordinated knowledge exchange and collaboration between researchers, industry, producers, and government, as well as limited access to education and training in seaweed aquaculture and biotechnology. There are also concerns over data and information sharing from an intellectual property and confidentiality perspective. The industry would benefit from increased collaboration, education, and knowledge sharing.

Product standards and traceability: Standardized testing protocols and certification schemes are absent. Variations in definitions and specifications across countries and over time have resulted in considerable challenges regarding market access; therefore, implementing a unified classification system could offer substantial advantages, including broader product credibility and access to premium markets.

Regulatory and policy frameworks: Many geographies have complex permitting processes, lack streamlined regulations, and do not recognize the benefits of seaweed biostimulants. Advances in streamlining permitting and integrating seaweed biostimulants into environmental credit systems would create a more favorable and solid regulatory and policy framework.

Sustainability characterization: The use of seaweed biostimulants and the cultivation of seaweeds can clearly offer wider sustainability advantages to primary production in regions where they are implemented. However, improved methods are necessary to effectively demonstrate and measure these benefits; focused research and LCAs are required at global, regional, and/or local levels to enable performance comparability.

Market development and incentives: Some countries lack government-sponsored incentives, subsidies, and grant programs to support the adoption of a market for seaweed biostimulants. They also lack strategies for reducing reliance on imported seaweed products and strengthening domestic supply chains. Plus, research is lacking on financial innovation and the appropriate blended finance vehicles to support seaweed product development. More demand-generation activities are needed, as well as more research on financial innovation and the appropriate blended finance vehicles to support seaweed product development.

Workforce skills: The current workforce lacks widespread expertise in seaweed aquaculture, biotechnology, and processing, highlighting a key gap in capacity development.

Bridging these knowledge gaps via targeted research, policy reform, and capacity development is critical for fostering sustainable growth and enhancing the global competitiveness of the seaweed biostimulant industry. Notably, many of these challenges can be addressed most effectively through collaborative efforts (see Table 7).

Table 7. R&D priority areas organized by sector/sectoral relevance.

Stakeholder	Sectoral R&D focus area
Government (national & regional)	▪ Include seaweed biostimulants in strategic industry planning. ▪ Develop policies to improve access to seaweed aquaculture. ▪ Offer subsidies, incentives, and R&D grants for seaweed farming that include longer terms and coordinated grant cycles. ▪ Manage wild-harvest impacts and help businesses shift to aquaculture. ▪ Streamline permits, licensing, and export/import regulations. ▪ Link agriculture and aquaculture through targeted research and advocacy. ▪ Fund focused R&D to address technical challenges and build robust hatchery networks and supply chains. ▪ Provide support for large-scale validation trials. ▪ Facilitate platforms for data and knowledge sharing.
Private investors (nongovernmental organizations, funders, & industry associates)	▪ Focus R&D on solving technical and commercial challenges. ▪ Reduce seaweed costs while maintaining sustainability. ▪ Partner with industry, researchers, and government. ▪ Support policies to grow supply chains and markets. ▪ Offer patient, non-dilutive catalytic capital that is potentially linked to offtake or trial data (e.g., supply chain finance). ▪ Educate a wider investor base to help with investor literacy on complex R&D and technical details.
Seaweed farmers	▪ Partner with agriculture, research, and government. ▪ Expand markets with industry and government; assess risks and opportunities. ▪ Target R&D to solve technical and commercial challenges, support national hatchery networks, improve farming, and strengthen supply chains. ▪ Support policies that boost sector growth and market development.
Agricultural farmers	▪ Inform priorities and provide opportunities for farm-scale biostimulant trials, which may include seeking provisions for subsidies or insurance. ▪ Support policies for sector growth, supply chains, and markets. ▪ Partner with industry, researchers, and government.
Research organizations	▪ Study core product qualities and unique benefits. ▪ Confirm pre-commercial product benefits. ▪ Create new processing methods, products, and applications. ▪ Advance research linking agriculture and aquaculture through targeted studies, improved techniques, product development, and the validation of effectiveness and sustainability.
Supply chain partners	▪ Partner with industry, researchers, and government. ▪ Develop products and processes. ▪ Clarify value chains and sustainability. ▪ Enhance market access by advancing relevant standards, certifications, and regulations.

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Blue Dot Sea Farms, Hood Canal, WA, U.S. © Blue Dot.

Appendix A:
Participants at the Seaweed Biostimulants Roundtable, October 2025

Name	Organization
Heidi Alleway	The Nature Conservancy
Luke Ansell	Algapelago Marine
Humphrey Atkinson	Algapelago
Azzedine Badis	Global Seaweed Coalition
Drusila Esther Bayate	Fisheries, Department of Agriculture, the Philippines
David G. Beaudreau, Jr.	DC Legislative and Regulatory Services, Inc.
Toby Berkman	Consensus Building Institute
Toby Sheppard Bloch	GreenWave
Anouk Bosman	Kelp Blue
Clare Bradley	AgriSea New Zealand & AgriSea Seaweed, Corp.
Tane Bradley	AgriSea New Zealand Seaweed
Nigel Bradly	EnviroStrat, Ltd.
Erin Bremner-Mitchell	Cascadia Seaweed
Carolina Camus	Universidad de Los Lagos
Geoffrey Chapin	Carbonwave
Tessa Charupatanapongse	Potato Impact Partners
Jingjie Chu	The World Bank
John D. Coates	University of California Berkeley, International Bioeconomy & Macroalgae Center
Jason Cole	MacroCarbon
Anoushka Concepcion	Global Seaweed Coalition
Megan Considine	The Nature Conservancy
Michael Coogan	University of New Hampshire
Thiago Correa	University of California Berkeley, International Bioeconomy & Macroalgae Center
Elizabeth Cottier-Cook	Scottish Association for Marine Science
Alan T. Critchley	Verschuren Centre
Melanie Cueff	Global Seaweed Coalition
Cristhian Danko	The Nature Conservancy
Paul Dobbins	World Wildlife Fund
Johanan Dujon	Algas Organics

Juan Gonzalo Flores	International Finance Corporation
Rod Fujita	Ocean Innovations
Adrian Gagu	International Finance Corporation
Robert Galbraith	Builders Vision
Dale Galvin	Global Fund for Coral Reefs / Pegasus Capital
Arash Ghale	Rodale Institute
Natalio Godoy	The Nature Conservancy
Stephane Granato	Southeast Conference Alaska
Peter Green	Hatch Blue
Ólavur Gregersen	Ocean Rainforest
Donna Hazard	Vital Ocean Ventures
Sophia Herrou	International Finance Corporation
Nick Hill	Coast 4C
David Hiltz	Hiltz BioAg Consulting
Shannon Hood	Conservation International
Aaron Huang	OoNee
Patrik Huber	Mawimbi Ocean Innovations, Ltd.
Alaine Janosy	Nestle Purina PetCare
Keith Jones	Biological Products Industry Alliance
Harrison Charo Karisa	The World Bank
Jeehye Kim	The World Bank
Adrianna Kochanska	Ocean Rainforest
Conner Lachenbruch	Conservation International
Colin Lanzl	MarinElixirs
Guillaume Lefranc	Acadian Seaplants
Annie Li	World Wildlife Fund
Fernanda Lopez	International Finance Corporation
Catriona Macleod	University of Tasmania
Susan McCarthy	World Wildlife Fund
Doug Middleton	Ocean Organics
Nikhil Neelakantan	Ocean Visions
Sergey Nuzhdin	University of Southern California / Kelp Ark
Susan Otieno	Aquaculture and Fisheries, Kenya
Utsav Oza	Sea2Carbon

Hannah Packman	The Nature Conservancy
Todd Paige	World Wildlife Fund
Virginia Pan	SWEN Blue Ocean
Valentin Pitiot	Kelp Blue
Payam Pourtaheri	AgroSpheres
Vivek Prasad	The World Bank
Nichole Price	Bigelow Center for Seafood Solutions
Maria Gabriela Reyes Calderin	TIDE, C.A
Jennifer Rix	Fertum USA (U.S. Subsidiary of Patagonia Biotecnología)
Michael Y. Roleda	University of the Philippines, Marine Science Institute
Aly Rose	Millbor Foundation
Andrew Rose	Chesapeake Sun
Whitney Rottman	Wildflower Ventures
George Seaver	George Seaver
Mirko Serkovic	The World Bank
Alex Shapiro	World Wildlife Fund
Pushp Sheel Shukla	Sea6 Energy Private Limited
William Soid	TIDE, C.A.
Sofia Soto Reyes	Consensus Building Institute
Thew Suskiewicz	Atlantic Sea Farms
Bernice Tang	Potato Impact Partners
Miguel Torres	International Finance Corporation
Elymi Ar-J S. Tunacao	Bureau of Fisheries and Aquatic Resources, the Philippines
Taylor Voorhees	The Nature Conservancy
Sarah Wan-Yau	Potato Impact Partners
Tiffany Waters	The Nature Conservancy
Gracie White	Conservation International Ventures
Michael Williamson	Cascadia Seaweed
Michael Wironen	The Nature Conservancy
Charles Yarish	University of Connecticut / Woods Hole Oceanographic Institution / The GreenWave Organization

Appendix B:

Seaweed biostimulants roadmap: Key anticipated outcomes and outputs

Short term (Year 1) See Table 1 for details.	Medium term (Years 1–3) See Table 2 for details.	Long term (Years 3–5) See Table 2 for details.
Connect the community.		
▪ Collaboration facilitated. ▪ Needs clarified. ▪ Knowledge exchange developed.	▪ Ongoing collaboration and R&D infrastructure established. ▪ Mechanisms for sharing cost-benefit / return on investment information developed.	▪ Collaboration infrastructure reviewed. ▪ Next-stage R&D considered. ▪ Universal business plan created.
Develop products and the market overall.		
▪ Data collated. ▪ Financing approaches for industry growth assessed. ▪ Plans to strengthen domestic supply chains developed. ▪ Research and development (R&D) to optimize key traits or discover new species (i.e., bioprospecting) outlined.	▪ Reference database developed. ▪ Government and private sector incentives enhanced. ▪ Extraction and processing methods to maximize benefits developed. ▪ Farmer-focused educational programs developed. ▪ R&D to optimize key traits and bioprospecting initiated.	▪ Next-level studies and R&D conducted. ▪ Farmer-focused educational programs implemented. ▪ Investment with new finance approaches encouraged.
Develop capacity/capability.		
▪ R&D needs to encourage aquaculture and reliable seedstock specified. ▪ Workforce capacity assessed.	▪ Aquaculture/seedstock supply plan initiated. ▪ Better practices created. ▪ Workforce capacity-building initiated. ▪ Biorefinery extraction options evaluated.	▪ Long-term biosecure seedstock established. ▪ Better practices updated and implemented. ▪ Collaborative approach to education and training implemented. ▪ Industry output with biorefinery extraction enhanced.
Enhance governance (regulatory and policy frameworks).		
▪ Standardization and traceability plan developed. ▪ Certification gaps addressed. ▪ Simplified permitting and policy guidance identified. ▪ Credit-system integration explored.	▪ Unified standards developed. ▪ Simplified permitting and regulations recommended. ▪ Credit-system integration explored.	▪ Standards established. ▪ Adoption of standards encouraged and scaled to multiple geographies.
Advance a sustainability proposition.		
▪ Sustainability data and gaps assessed. ▪ Life cycle assessment (LCA) options for measuring sustainability researched.	▪ Portfolio of sustainability analyses and LCAs developed.	▪ Benefits and impacts of an expanded biostimulants industry evaluated and quantified.

Review & evaluation ongoing: Regularly assess progress of R&D efforts, market trends, & regulatory developments. Adjust timelines & strategies as necessary based on findings & stakeholder feedback.

Increasing: Trust & strategic alignment. Industry relevance & economies of scale. Opportunities & sustainability.

Appendix C:
Selected studies demonstrating specific benefits and crop applications

The following table is based on data from the U.S. Department of Agriculture (USDA) and has been updated with permission. Adapted from Price et al. (2024).

	Learned benefit of seaweed-based biostimulant application				
Crop name	**Germination/ growth efficiency**	**Improved yield/ quality**	**Abiotic stress resistance**	**Enhanced soil quality**	**Abiotic stress – manipulated**
Apple		Mousavi et al. (2024)			
Arugula	Candido, Boari, et al. (2023) and Candido, Cantore, et al. (2023)	Candido, Boari, et al. (2023)			Candido, Boari, et al. (2023) and Candido, Cantore, et al. (2023)
Avocado	Arioli et al. (2024)	Arioli et al. (2024)			
Barley	Goñi et al. (2021)	Goñi et al. (2021)			
Basil	Consentino et al. (2023)	Consentino et al. (2023) and Raj et al. (2022)		Raj et al. (2022)	Consentino et al. (2023)
Beet	Pačuta et al. (2024)	Pačuta et al. (2024)			
Cabbage	Rengasamy et al. (2016)		Rengasamy et al. (2016)		
Cannabis	Wise et al. (2024)				
Canola	Nichol et al. (2023)				Nichol et al. (2023) and Shahriari et al. (2021)
Carrot		Pobereżny et al. (2020) and Szczepanek et al. (2015)			
Collard greens		Sandhu et al. (2018)			
Cowpea	Gyogluu Wardjomto et al. (2023)	Gyogluu Wardjomto et al. (2023)			
Cucumber		Zamljen et al. (2024).			
Eggplant	Al-Bayati et al. (2020)	Al-Bayati et al. (2020) and Pohl et al. (2018, 2019)			Al-Bayati et al. (2020)
Fenugreek	Dehkordi et al. (2021)	Dehkordi et al. (2021)			Dehkordi et al. (2021)

	Learned benefit of seaweed-based biostimulant application				
Crop name	**Germination/ growth efficiency**	**Improved yield/ quality**	**Abiotic stress resistance**	**Enhanced soil quality**	**Abiotic stress — manipulated**
Garden cress	Michalak and Baśladyńska (2021)	Michalak and Baśladyńska (2021)			
Gooseberry	Figueiredo et al. (2021)				Figueiredo et al. (2021)
Grape	Frioni et al. (2021)	Arioli et al., (2021), Frioni et al. (2018, 2019), and Leogrande et al. (2022)			Frioni et al. (2021)
Grass	Godlewska and Ciepiela (2016) and Quille et al. (2022)				
Green bean					Petropoulos et al. (2020)
Hydrangea					De Clercq et al. (2023)
Kale	Pacheco et al. (2021) and Sandhu et al. (2018)				
Kiwifruit	Rana, Sharma, et al. (2023)	Rana, Sharma, et al. (2023)			
Lettuce	Chaski and Petropoulos (2022), Di Mola et al. (2019), Moncada et al. (2022), Rasouli et al. (2022), Sandhu et al. (2018), Velasco-Clares et al. (2024), and Wang et al. (2022)	Di Mola et al. (2019, 2020) and Velasco-Clares et al. (2024)			Chaski and Petropoulos (2022)
Maize	Fayzi et al. (2020) and Trivedi, Vijay Anand, Vaghela, and Ghosh (2018)	Trivedi, Vijay Anand, Kubavat, et al. (2018); Trivedi, Vijay Anand, Vaghela, and Ghosh (2018); Trivedi, Vijay Anand, et al. (2022); and Trivedi, Kumar, et al. (2022)	Tinte et al. (2022) and Trivedi et al. (2021)		Kumar et al. (2020); Trivedi, Vijay Anand, Kubavat, et al. (2018); and Trivedi, Vijay Anand, et al. (2022)

	Learned benefit of seaweed-based biostimulant application				
Crop name	Germination/ growth efficiency	Improved yield/ quality	Abiotic stress resistance	Enhanced soil quality	Abiotic stress — manipulated
Marigold	Tavares et al. (2020)				
Milkweed	Bahmani Jafarlou et al. (2021, 2022, 2023)				Bahmani Jafarlou et al. (2021, 2023)
Millet	Rathinapriya et al. (2020)	Rathinapriya et al. (2020)			
Mint	Laribi et al. (2023)	Chaski et al. (2023)			Chaski et al. (2023)
Moth bean	Verma et al. (2021)				
Mung bean	Di Filippo-Herrera et al. (2021); Hernández-Herrera, Hernández-Carmona, et al. (2022); and Karthik and Jayasri (2023b)	Karthik and Jayasri (2023b)			
Mustard greens	Goyal et al., (2023) and Sandhu et al. (2018)	Goyal et al., (2023)			Goyal et al., (2023)
Oats		Gurmani et al. (2021)			
Oil palm	Kresnawaty et al. (2022)				
Oilseed rape	Billard et al. (2014), Siwik-Ziomek and Szczepanek (2018), and Szczepanek et al. (2017)	Łangowski et al. (2019)			
Okra	Aremu et al. (2022), Khan et al. (2022), Makhaye et al. (2021), and Muniswami et al. (2023)	Aremu et al. (2022) and Muniswami et al. (2023)			Khan et al. (2022)
Olive		Leogrande et al. (2022)			
Onion	Gupta et al. (2021)	Gupta et al. (2021)			

	Learned benefit of seaweed-based biostimulant application				
Crop name	**Germination/ growth efficiency**	**Improved yield/ quality**	**Abiotic stress resistance**	**Enhanced soil quality**	**Abiotic stress — manipulated**
Pea	Shukla et al. (2024)				
Pepper	Ali et al. (2022, 2023) and Ozbay and Demirkiran (2019)	Ali et al. (2022, 2023), Arthur et al. (2023), and Renaut et al. (2019)	Dalal et al. (2019)		
Pigweed	Kumareswari and Rani (2016) and Ngoroyemoto et al. (2020)				
Potato	Gaynatulina and Khasbiullina (2021) and Wadas and Dziugieł (2019)	Wadas and Dziugieł (2019, 2020)			
Radish	Gul et al. (2023)				Gul et al. (2023)
Rice	Shahzad et al. (2023)	Shahzad et al. (2023)			Shahzad et al. (2023)
Rice bean	Pascual et al. (2021)	Pascual et al. (2021)			
Soybean	da Silva et al. (2024); Kocira et al. (2018); and Mathur et al. (2015)	Franzoni et al. (2023); Kocira et al. (2018); Krawczuk et al. (2023); Łangowski et al. (2021); Mathur et al. (2015); and Meyer et al. (2021)	Shukla et al. (2018)		da Silva et al. (2024) and do Rosário Rosa et al. (2021)
Spinach		La Bella et al. (2021) and Rouphael et al. (2018)			
Strawberry	Rana, Lingwal, et al. (2023) and Soppelsa et al. (2019)	Mattner et al. (2023); Rana, Lingwal, et al. (2023); Soltaniband et al. (2022); Soppelsa et al. (2019); and Weber et al. (2018)			
Sugarcane	Karthikeyan and Shanmugam (2017) and Singh et al. (2023)	Jacomassi et al. (2022), Karthikeyan and Shanmugam (2017), and Singh et al. (2018, 2023)			Jacomassi et al. (2022)

	Learned benefit of seaweed-based biostimulant application				
Crop name	Germination/ growth efficiency	Improved yield/ quality	Abiotic stress resistance	Enhanced soil quality	Abiotic stress — manipulated
Sunflower	Santos et al. (2019)				
Swiss chard	Sandhu et al. (2018)				
Texas bluebell	Velasco-Ramírez et al. (2020)				
Thale cress	Chen et al. (2024), Jensen and Jorgensen (2022), and Shefer et al. (2022)	Chen et al. (2024)	Rasul et al. (2021)		Chen et al. (2024) and Ugena et al. (2018)
Tomato	Ali et al. (2022, 2023); Bentley et al. (2022); Borella et al. (2023); Domingo et al. (2023); González-González et al. (2020); Hernández-Herrera, Sánchez-Hernández, et al. (2022); Karthik and Jayasri (2023a); Mazepa et al. (2021); Moncada et al. (2022); Polo and Mata (2018); and Villa e Vila, Rezende, et al. (2023)	Abdelkader et al. (2021); Ahmed et al. (2023); Ali et al. (2023); Borella et al. (2023); Campobenedetto et al. (2021); Chanthini et al. (2019); Colla et al. (2017); Karthik and Jayasri (2023a); Lakshmi et al. (2023); Liava et al. (2023); Polo and Mata (2018); Renaut et al. (2019); Subramaniyan et al. (2023); Vaghela et al. (2023); Villa e Vila, Marques, et al. (2023); and Villa e Vila, Rezende, et al. (2023)	Carmody et al. (2020) and Zhang et al. (2023)		Ahmed et al. (2023); Ali et al. (2024); Borella et al. (2023); Campobenedetto et al. (2021); Domingo et al. (2023); Gil-Ortiz et al. (2023); Hernández-Herrera, Sánchez-Hernández, et al. (2022); Kalozoumis et al. (2021); Liava et al. (2023); Morales-Sierra et al. (2023); Top et al. (2023); Vaghela et al. (2023); and Villa e Vila, Marques, et al. (2023)
Wheat	Mohammed Ali and Mohammed (2024), Sooväli et al. (2018), and Stamatiadis et al. (2021)	Knapowski, et al. (2019), Matysiak et al. (2018), Sooväli et al. (2018), and Stamatiadis et al. (2021)			Sharma et al. (2019)

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