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Effect of Seaweed Extract on Growth and Yield of Chickpea (*Cicer arietinum* L.)

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Abstract

The use of seaweed extract has become an environmentally sustainable alternative biostimulant that has shown great potential to improve crop growth, productivity, and stress resistance in sustainable agriculture. Due to its nutritional profile and high protein content, chickpea (*Cicer arietinum* L.) is one of the significant legumes cultivated around the world and produces the desired response towards bioactive compounds found in seaweed extracts, like plant growth regulators, amino acids, vitamins, micronutrients, and polysaccharides. This review aims to bring to light the impact of seaweed extract application on chickpea germination, vegetative growth, physiological traits, nodulation, flowering, yield attributes, and seed quality. The results showed seaweed extract treatment in foliar and seed promotes the development of roots, chlorophyll, nutrient uptake, photosynthetic efficiency, and antioxidant activity, resulting in increased plant vigor and productivity. Use of seaweed-based biostimulants also enhances drought resistance, water use efficiency, and increases resistance to abiotic stress conditions. An application of seaweed extract at critical growth stages has been reported in several studies to enhance pod formation, seed weight, biological yield, and harvest index. Seaweed extract is beneficial in enhancing crop performance as well as soil microbial activity and reducing synthetic fertilizer usage, which has a positive impact on sustainable crop production. Future research is needed to further develop application methods, concentrations, timings, and combine seaweed extracts with nutrient management strategies to achieve better chickpea productivity across a range of agroclimatic situations.

Keywords: Seaweed extract, chickpea, biostimulant, growth enhancement, sustainable agriculture

1. Introduction

Chickpea (*Cicer arietinum* L.) is an important grain legume and is a significant contributor to food and nutritional security, particularly in the semi-arid regions where it is a major source of dietary protein and is an integral part of cereal-based cropping systems. Increase in food demand, and limited availability of arable land and water, have created a need to improve the productivity and sustainability of chickpea production in variable and stressful environments, which has been the focus of current crop improvement. Meanwhile, the traditional reliance on synthetic fertilizers and agrochemicals has been called into question, as their use contributes to soil degradation, pollution of the environment, and greenhouse gas emissions, calling for alternative strategies to sustainable nutrient management that can endorse or enhance yields without increasing external inputs (Sujeeth *et al.*, 2022) ^[15]. Plant biostimulants have been seen to be emerging as a potential tool in this context. Biostimulants are products that activate the plant's nutrition processes without containing nutrients, which help increase the efficiency of nutrient use, tolerance to abiotic stress, quality of crops, and increase nutrient availability in the rhizosphere (Kumari *et al.*, 2023; Sujeeth *et al.*, 2022) ^[9, 15]. These are of two types, one microbial and the other non-microbial, with seaweed extracts being one of the most widely researched and used groups of non-microbial formulations in commercial agriculture (Ali *et al.*, 2021; Kumari *et al.*, 2023) ^[9]. Seaweed-based biostimulants are complex formulations, which are mainly composed of macroalgae, and consist of phytohormones, polysaccharides, proteins, polyphenols, vitamins, and mineral elements. These bioactives have several agronomic advantages, such as better germination, vegetative growth, rooting, photosynthesis, nutrient uptake, and yield, under optimal and stress conditions—including drought, salinity, and temperature extremes—often. Other benefits of using seaweed extracts include the ability to regulate soil and root microbes,

improve soil structure and fertility, and be easily incorporated into reduced conventional input application systems, which is especially advantageous for integrated and organic production systems (Kumari *et al.*, 2023; Sujeeth *et al.*, 2022) ^[9, 15]. Since chickpea plays a vital role in low-input and stress-prone environments, testing the use of seaweed extract as a natural biostimulant appears to be a promising strategy to boost growth and yield while promoting resource-efficient and environmentally friendly chickpea production systems (Ali *et al.*, 2021; Rabhi *et al.*, 2025) ^[1, 12].

2. Seaweed Extract: Composition and Properties

Seaweed extracts are also extensively applied in agriculture as biostimulants due to their richness in various organic compounds, plant hormones, and micronutrients that promote plant growth, yield, and stress resistance. They have a direct impact on the nutritional inputs as well as an indirect impact by regulating plant metabolism and defense responses. The most prominent commercial macroalgae sources for seaweed used in agriculture are brown seaweed (Phaeophyceae), red seaweed (Rhodophyta), and green seaweed (Chlorophyta), with brown seaweeds like *Ascophyllum nodosum*, *Ecklonia maxima*, *Macrocystis pyrifera*, and *Durvillaea potatorum* being the primary sources for crop biostimulant extracts. The selection of these species is due to their abundance and high hormone content along with polysaccharides and mineral content, and their extracts have been proven to have regular and positive effects on seed germination, root growth, biomass accumulation, and stress tolerance in different crops. The bioactive compounds present in seaweed extracts are mostly organic compounds such as polysaccharides (e.g., alginates, laminarins, fucoidans, carrageenans, ulvans), polyphenolics (e.g., phlorotannins), fatty acids, sterols, carotenoids, betaines, amino acids, peptides, proteins, lipids, vitamins, and trace minerals. The components are dependent on the type and species of seaweed, season, and extraction method, and have complex interactions where extracts of the whole seaweed are generally more effective than isolates of these components (Ali *et al.*, 2021) ^[1].

Seaweed extracts further contain plant growth regulators that have a hormone-like activity, such as auxins (e.g., indole acetic acid), cytokinins, gibberellins, abscisic acid, brassinosteroids, jasmonates, salicylates, and polyamines, as well as betaines and signal peptides. They are also rich in

micronutrients like Fe, Cu, Zn, Co, Mo, Mn, and Ni, which play a role in enzyme functions and plant nutrition (Kumari *et al.*, 2023) ^[9]. These mixtures have different impacts in plants, including: (i) phytostimulation: root or shoot growth, cell division and elongation, and synthesis and yield of chlorophyll; (ii) elicitation and priming of defense: triggering defense signaling, upregulating defense related genes and increasing antioxidant activity; (iii) improved nutrient uptake and soil effects: compounds such as alginates and polyuronides improve soil structure, water holding capacity and soil microbial activity, which increases nutrient uptake and availability (Ali *et al.*, 2021; Kumari *et al.*, 2023) ^[1, 9].

3. Methods of Seaweed Extract Application in Chickpea

Seaweed extract may be used as a seed treatment/priming, sprayed on the foliage, or added to the soil as a treatment to enhance germination, vigor, nutrient uptake, stress tolerance, and yield of chickpea. Recommendations for the use of seaweed biostimulants on crops include general recommendations, which can be transferred to chickpeas with caution (Table 1). The foliar application is often identified as more effective than soil application due to faster uptake through foliar compared to soil, where particles can take up and bind the components of the composition, rendering them unavailable for immediate uptake by the roots. For many crops, low concentration foliar sprays at a 10–14 day interval are recommended to preserve the biostimulant activity during critical growth stages (Ali *et al.*, 2021) ^[1]. Seaweed extract or brown seaweed materials (fresh, dried, granules, powders, composts) when applied to the soil can benefit soil physical, chemical, and biological properties, including enhancing soil porosity, water holding capacity, and microbial activity, which promote root growth and nutrient uptake (Sariñana-Aldaco *et al.*, 2025) ^[14]. However, repeated applications and high doses are suggested in the field, which will increase the cost of application, and soil application with more efficient foliar sprays is recommended (Ali *et al.*, 2021; Sariñana-Aldaco *et al.*, 2025) ^[1, 14]. These broad guidelines suggest that chickpea-specific trials of establishing seed with dilute seaweed solutions to improve establishment, then applying low rates of foliar seaweed sprays strategically (at vegetative growth, flowering, and pod filling) and, if economically viable, applying occasional soil seaweed sprays, could be integrated and subsequently calibrated.

Table 1: Seaweed Application Methods and Typical Ranges

Method	Practical approach (generic crops)	Typical concentration/frequency	Notes for chickpea adaptation (conceptual)	Sources
Seed treatment/seed priming	Soak seeds in dilute liquid extract, then surface-dry before sowing	Not numerically specified; plant-based biostimulants are widely explored for seed priming	Used to enhance germination, vigor, and early stress tolerance; requires crop-specific optimization	(Wazeer <i>et al.</i> , 2024) ^[17]
Foliar spray	Spray aqueous extract directly on foliage at vegetative and reproductive stages	≤0.05% (v/v) is often reported as optimal; applied every 10–14 days	Can be targeted to branching, flowering, and early pod set stages to support growth and yield	(Ali <i>et al.</i> , 2021) ^[1]
Soil drench/fertigation	Apply solution to soil or growing medium via drenching, drip, or fertigation	Rates vary; soil application often requires higher amounts and multiple applications	Useful to improve soil structure and root zone conditions, but costlier due to larger volumes	(Ali <i>et al.</i> , 2021) ^[1]

4. Effect on Seed Germination and Early Seedling Growth

During the earliest stages of plant development, seaweed extracts act as potent biostimulants on seed germination,

seedling vigor, root system architecture, and plant establishment. They are not only caused by the presence of various plant-based polysaccharides, hormones, or other bioactive molecules, but also by the effect of a complex

nutritional combination. Seaweed extracts have been used in crops numerous times to improve germination percentage. Of all the products tested, those derived from *Ascophyllum nodum* exhibited the greatest germination rate and percentage in barley, maize, onion, and rice, sometimes by facilitating the absorption of water, inducing an amylase activity that is independent of gibberellic acid, and lowering seed dormancy. In barley, priming with *A. nodosum* extract led to an increase in the germination rate and availability of oxygen to the embryo, and a decrease in the microbial contamination on the seed surface (Kumari *et al.*, 2023) ^[9]. Seaweed extracts also stimulate seedling growth and the development of roots. Early applications have been found to enhance root length, root density and shoot growth in many species such as tomato, cucumber, onion, maize, strawberry, spruce, and several ornamentals. These responses are associated with increased cell division, elongation, and lateral root production, involving the activation of genes associated with hormone-like activity, such as auxins, cytokinins, gibberellins, and nutrient transport. Seaweed extracts significantly enhance early plant establishment by stimulating more rapid germination and deeper, more robust, and branched root systems, as well as greater early shoot development. The biomass, chlorophyll content, water status, and nutrient uptake of treated seedlings are increased, leading to higher survival rates, reduced transplant shock, and more uniform, competitive stands in the field (Ali *et al.*, 2021; Kumari *et al.*, 2023) ^[1, 9].

5. Effect on Vegetative Growth and Physiological Traits

Seaweed extracts are effective biostimulants that have significant effects on vegetative growth and physiological characteristics, and are likely to affect plant height, leaf growth, photosynthesis, biomass production, and nutrient uptake. The evidence is mainly from a variety of crop species, and not from chickpea per se, but rather the processes are common to many higher plants. In many crops, seaweed products enhance overall vegetative growth, including plant height and stem diameter and the development of the root system, leading to larger shoot systems. In a few species, foliar/brown algal extract application (*Ascophyllum nodosum*) resulted in an increase in plant height, number of leaves, aerial and root biomass, as well as a higher branching potential (meaning plant canopy formation) (Sujeeth *et al.*, 2022) ^[15]. Seaweed treatments always increase leaf area and chlorophyll content, which are important indicators of photosynthetic capacity. Extracts have been reported to produce an increase in the number, area, and concentration of chlorophyll in a wide range of crops, such as tomato, eggplant, French bean, petunia, and ornamental plants, resulting in greener and denser leaves (Ali *et al.*, 2021; Sujeeth *et al.*, 2022) ^[1, 15]. The changes are caused by hormone changes (auxin- and cytokinin-like activity) and nutrient status.

The chlorophyll content is correlated with better photosynthesis efficiency. *A. nodosum* extracts have been used in several applications to improve the net photosynthetic rate, stomatal conductance, and transpiration in normal and stress conditions, as well as increase fresh and dry biomass of shoots and roots (Ali *et al.*, 2021; Sujeeth *et al.*, 2022) ^[1, 15]. This improved photosynthetic efficiency has

positive impacts on biomass production. Seaweed extracts also enhance nutrient uptake and use efficiency, through root growth promotion, root architecture changes, and providing chelating polysaccharides and micro-elements. The combined application of *A. nodosum* extract to the leaves and seeds of leguminous crops like soybean showed an improvement in the mineral nutrition and internal N metabolism through the upregulation of macronutrient uptake and activities of essential enzymes of N metabolism (Sujeeth *et al.*, 2022) ^[15]. Seaweed-based biostimulants are likely to stimulate chickpea vegetative growth, canopy development, and physiological performance in similar ways to this.

6. Influence on Nodulation and Nitrogen Fixation

The potential effects of seaweed-based biostimulants on root nodulation, symbiotic nitrogen fixation, and soil microbial activity in legumes like chickpea are indirect, affecting the rhizosphere environment and the plant's physiology, rather than directly providing nitrogen. Seaweed extracts positively influence the root growth, root exudation, and the proliferation of beneficial microbial communities and thereby provide favorable conditions for *Rhizobium* infection and nodule formation. The polysaccharides and auxin-like compounds present in brown seaweed promote root system architecture and aggregation, resulting in greater root-soil contact and possible increased number of rhizobial infection sites and nodules per plant (Ali *et al.*, 2021; Kumari *et al.*, 2023) ^[1, 9].

As for symbiotic nitrogen fixation, there is a correlation between the development and longevity of the nodules and the activity of nitrogenase and the yield of total plant nitrogen. Infection, nodule organogenesis and maintenance of nodule function are marked by reviews of auxin (IAA) as playing a central role in all these processes and the use of auxin producing endophytic bacteria, which increases nodule number, leghemoglobin content, acetylene reduction activity, and total plant nitrogen (Hnini & Aurag, 2024) ^[7]. The auxin-like and cytokinin-like compounds present in seaweed extracts can act on similar pathways in host plants, and this may enable them to improve the efficiency of nodulation and nodule function, particularly under stress situations that inhibit biological nitrogen fixation (Ali *et al.*, 2021; Kumari *et al.*, 2023) ^[1, 9].

Application of seaweeds also has an impact on soil microbial activity and community structure. The polysaccharides and organic matter produced from seaweeds serve as substrates and signaling molecules, boosting microbial biomass, enzymatic activities, and concentrations of beneficial microorganisms, such as nitrogen-fixing and nutrient-cycling bacteria in the rhizosphere (Ali *et al.*, 2021; Yasmeen *et al.*, 2025) ^[1, 18]. This increased microbial activity helps to increase nutrient availability and soil structure, indirectly enhancing the effectiveness of *Rhizobium* – legume symbioses and nitrogen fixation in response to varying environmental conditions.

The integrated physiological and agronomic effects of seaweed extract biostimulants on chickpea growth, productivity, stress tolerance, and sustainability are summarized in Figure 1.

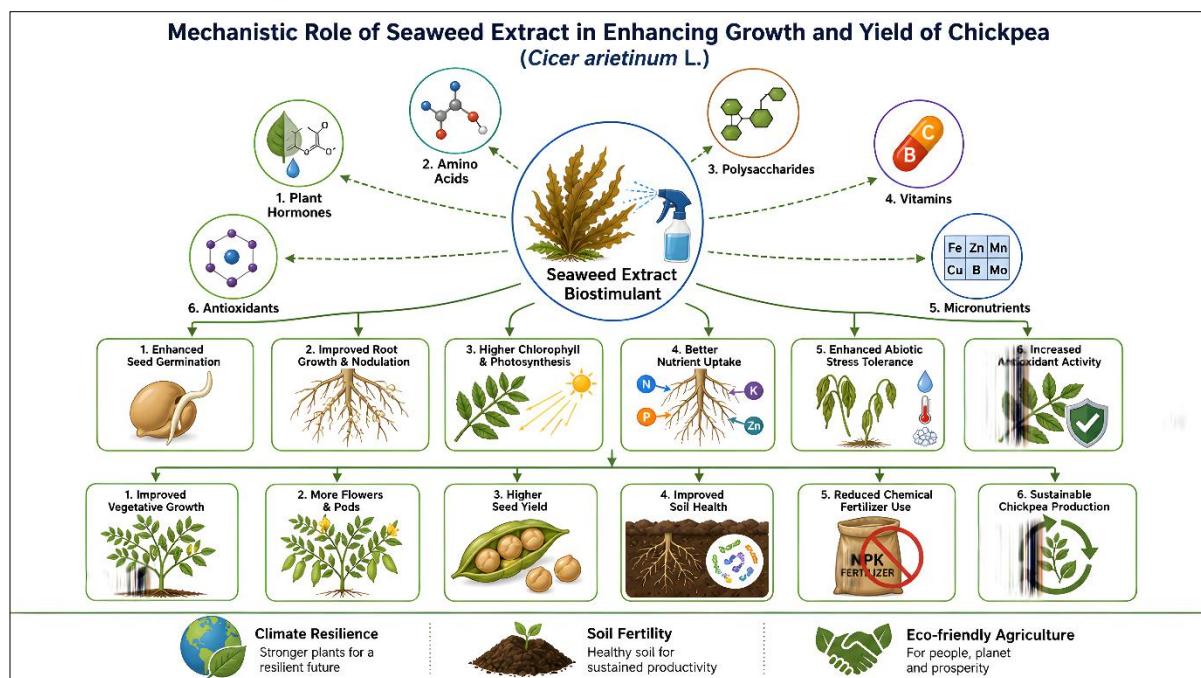


Fig 1: Mechanistic role of seaweed extract biostimulants in enhancing growth, physiology, stress tolerance, yield, and sustainability in chickpea (*Cicer arietinum* L.).

Seaweed extracts containing plant hormones, amino acids, polysaccharides, vitamins, micronutrients, and antioxidants improve seed germination, root growth and nodulation, chlorophyll synthesis, nutrient uptake, abiotic stress tolerance, and antioxidant activity, ultimately resulting in enhanced vegetative growth, higher flower and pod formation, increased seed yield, improved soil health, reduced chemical fertilizer use, and sustainable chickpea production.

7. Effect on Flowering, Yield Attributes, and Yield

The reproductive and yield parameters of many crops are improved by the use of seaweed-based biostimulants, making it a very promising application for chickpea flowering, pod set, and final yield. These complexes of hormones, polysaccharides, and nutrients are responsible for stimulating vegetative and reproductive growth, which can result in increased yields and better harvest indices. The higher pod or flower numbers per plant have been correlated

with improved branching, flowering intensity, and reproductive organ retention, which increases the number of pods or flowers per plant. In oilseeds and cereals, under stress, improved seed size and 100-seed weight are due to an increase in photosynthesis and uptake of nutrients and assimilate translocation to the developing seed (Mughunth *et al.*, 2024) ^[10]. The use of seaweed extracts to stimulate the canopy growth, root growth, and reproductive sink strength at the same time, which also helps to alleviate the abiotic stress, thus the overall grain and biological yield is increased (Ali *et al.*, 2021; Mughunth *et al.*, 2024) ^[1, 10]. For some root and grain crops, this is accompanied by an improvement in harvest index, which represents the proportion of total crop production that is utilized for crop economic products (Ali *et al.*, 2021) ^[1]. With proper timing and dosages (Table 2), similar improvements in flower and pod number, seed weight, grain yield, and harvest index are predicted with chickpea when seaweed extracts are used.

Table 2. Key reproductive and yield responses to seaweed biostimulants

Yield trait/stage	Typical effect of seaweed extracts on crops	Examples/notes	Sources
Number of flowers/pods or fruits	Increased flowering, fruit set, and number of pods or fruits per plant	Sweet pepper and pepper showed more flowers and higher fruit number with <i>Ascophyllum</i> -based sprays	(Ali <i>et al.</i> , 2021; Mughunth <i>et al.</i> , 2024) ^[1, 10]
Seed size/unit seed weight	Increased seed or fruit size; higher 1000-seed weight in some grain and oilseed crops	Mustard greens under heat stress had higher 1000-seed weight, siliqua number, and seed yield with <i>A. nodosum</i>	(Mughunth <i>et al.</i> , 2024) ^[10]
Grain or marketable yield	Consistent increases in grain/fruit yield across cereals, vegetables, and legumes	Wheat, rice, maize, soybean, spinach, tomato, and pepper all showed higher total or marketable yield	(Ali <i>et al.</i> , 2021; Mughunth <i>et al.</i> , 2024) ^[1, 10]
Biological yield/biomass	Greater total biomass (shoot + root), often under both normal and stress conditions	Increases in biomass were recorded in broccoli, spinach, grasses, tomato, eggplant, and legumes	(Ali <i>et al.</i> , 2021; Mughunth <i>et al.</i> , 2024) ^[1, 10]
Harvest index	Improved partitioning of biomass to harvestable organs (seeds, roots, fruits) in some crops	Carrot showed increased harvest index with brown seaweed extract; cereals showed higher grain proportion	(Ali <i>et al.</i> , 2021) ^[1]

8. Role in Abiotic Stress Management

Seaweed-based biostimulants are important to assist plants during abiotic stress conditions of drought, salinity, and extremes of temperature. Their effects are primarily due to changes in the water relations and redox (oxido-reduction) balance and/or metabolism of protective compounds of plants, rather than mere fertilization. Algal/seaweed biostimulants have consistently proven to enhance tolerance under drought stress, contributing to the accumulation of more biomass, higher uptake of nutrients, and higher water-use efficiency, primarily by boosting the ability of plants to increase photosynthesis and to better regulate stomatal closure (Vangenechten *et al.*, 2025; Ali *et al.*, 2021) ^[16, 1]. Biochemically, the plants grown under drought conditions containing algal products accumulate higher amounts of osmoprotectants (proline, soluble sugars) and enzymatic and non-enzymatic antioxidants, thereby maintaining cell turgor, protecting cell membranes, and sustaining growth under drought conditions (Vangenechten *et al.*, 2025) ^[16]. Mitigation is more species-specific for salinity stress. In the majority of cases algal biostimulants can induce recovery of salt stressed plants in terms of morphological and physiological aspects, the biochemical responses are variable: the ones that are increased may relate to the increase of the osmoprotectants or the antioxidants (a classical tolerance route), while the ones that are reduced can lead to a decrease in the perception of stress through mechanisms that have not been fully clarified (Vangenechten *et al.*, 2025) ^[16]. In all cases, salinity tolerance is associated with enhanced ion and osmotic regulation, decreased oxidative stress, and growth benefits under saline conditions. Heat stress mitigation via algal or seaweed biostimulants has received less attention and is still a significant research gap, but existing research indicates that these biostimulants can influence plant morphology, physiology, and biochemistry in response to high temperatures, in part through similar mechanisms of antioxidant and osmotic adjustment observed in drought and salinity stress. (Vangenechten *et al.*, 2025) ^[16].

9. Effect on Soil Health and Sustainability

The strong interactions between seaweed-based biostimulants and soil conditioners and the soil's physical, chemical, and biological properties have ramifications on soil fertility, microbial activity, fertilizer requirements, and sustainability in the long-term. There is a good deal of evidence from brown seaweed extracts (*Ascophyllum nodosum*) and macroalgae, which are applied as extracts, compost, powder, or granules. In the soil, brown seaweeds provide minerals and complexing compounds (alginate, fucoidan, laminarin, mannitol), which can help to improve soil structure and porosity, aggregation, and water holding capacity (Yasmeen *et al.* 2025) ^[18]. The input of alginate creates a gel-like matrix and improves aeration and root penetration, while organic matter will improve soil fertility and resilience through cation exchange and nutrient retention (Yasmeen *et al.*, 2025) ^[18]. The same advantages are reported for various amendments derived from seaweeds, which have a positive effect on soil organic matter and soil stability, especially in degraded or nutrient-deficient soils (Yasmeen *et al.*, 2025) ^[18].

Seaweed products also stimulate the population and activity of microorganisms. Extracts and solid amendments change the soil and plant microbiomes, leading to an increase in the

beneficial microorganisms and enzymatic activities involved in nitrogen cycling and plant growth. Increased microbial flow and diversity in the rhizosphere help to improve the mineralization of organic nutrients, nutrient availability, and control of some soil stresses, and thus, enhance the biological activity and self-regulating capability of soil. Seaweed as inputs can partially replace or complement chemical inputs for better nutrient use efficiency, root development, and microbial-mediated nutrient cycling, which can lead to reduced application of synthetic NPK and sustainable yields. Seaweed-based products have potential applications in sustainable agriculture due to their organic nature, compatibility with other inputs, and ability to improve soil health, which can contribute to long-term soil fertility, lower pollution, and agriculture that is more resilient (Ali *et al.*, 2021; Yasmeen *et al.*, 2025) ^[1, 18].

10. Economic Benefits of Seaweed Extract Application

Seaweed extracts generally have a strong economic advantage as a biostimulant that generates more productivity, nutrient savings, and fits into circular, “low waste” systems, but not necessarily as a nutrient. But on-farm cost-benefit data and/or formal profitability analyses are still limited. When considering the growth, yield, and stress tolerance of many crops, seaweed-based products have been consistently shown to improve these three parameters, which can lead to better gross economic returns per hectare, particularly where increased yield or improved quality is valued by the market (Arioli *et al.*, 2023; Ali *et al.*, 2021). In the field trials, for instance, *Gracilaria edulis*-derived plant bio stimulants enhanced the productivity of nine cash crops by 10-33%, which directly resulted in the improvement of the income-generating potential under the same land use and plant care conditions (Bhushan *et al.*, 2023) ^[3]. If achieved with relatively low product cost and application costs, such yield gains would typically lead to positive cost-benefit ratios.

The overall seaweed value chain is another factor that will influence profitability and farmer uptake. The reviews emphasize the potential of seaweed biomass for several high-value products (biostimulants, polysaccharides, nutraceuticals, etc.) and of the residue as soil amendments or other materials, contributing to the overall economic resilience, and hence to the investment in seaweed-based inputs for a circular bioeconomy (Ali *et al.*, 2021). However, the expensive cultivation, harvesting, and processing stages remain a challenge, and techno-economic evaluations come to the conclusion that the seaweed products market will be determined by the high cost of cultivation, harvesting, and processing at the upstream stage (Nakhate & Van Der Meer, 2021) ^[11]. From the point of view of resource use efficiency, seaweed extracts are said to be tools that can increase nutrient use efficiency, minimize the use of synthetic fertilizers, improve soil health, and promote sustainable productivity in stress situations. They can potentially increase the plant nutrient uptake and stress resistance, thereby maximizing output per unit of fertilizer, water, or degraded soil resource, at the core of long-term profitability and environmental performance of farms (Arioli *et al.*, 2023; Yasmeen *et al.*, 2025) ^[18].

11. Challenges and Limitations

Although seaweed extracts and derived products show great potential, they come with several challenges and limitations,

which need to be addressed for their wider use and uniform application in food, agriculture, and biotechnology. The main concern is the composition variability of the seaweed extract, which is due to biological and environmental factors. The chemical composition of seaweed (such as proteins, polysaccharides, phenolics, and other bioactives) can vary significantly with species, geographical origin, harvest time, maturity, and environmental factors locally, including nutrient availability or water temperature. This natural variation can pose difficulties in achieving consistency in the quality and effectiveness of extracts within and between different batches or sources. For instance, it has been found that bioactivities and products produced from the extraction of seaweed, even from closely related species, under the same extraction conditions, can vary significantly (Cardoso *et al.*, 2025) ^[5].

This variation in composition is directly affecting the standardization problem. There is no universal extraction protocol or benchmarks for quality assurance, which makes the results highly affected by operational parameters such as solvent type, temperature, extraction time, pre-treatment, and the scale of operation. Traditional extraction methods, such as maceration or water extraction, may yield low recovery rates or fail to recover thermolabile compounds, which are sensitive to heat and various extraction conditions, or some may not work for all seaweed species because of differences in cell wall structure and biochemical composition (Cardoso *et al.*, 2025) ^[5]. It follows that no one extraction method can ensure the maximum recovery of desired compounds from all seaweed species. This makes it more difficult to create standard products for commercialisation. Also, the lack of awareness and access. Many producers are hindered by technical problems with scaling up the laboratory or pilot-scale extraction processes to an industrial scale. The economic feasibility of large-scale production is also hindered by the high energy consumption and solvent usage, as well as the cost of equipment (Ghelichi & Jacobsen, 2025) ^[6]. Also, the regulatory issues of possible bioaccumulation of heavy metals or allergens in some of the seaweeds need to be carefully evaluated before products are accepted for general use. All these factors hamper the broad adoption of seaweed ingredients into food systems and/or in agriculture use.

Last but not least, there is a clear need for the recommendations to be location-specific. Due to the close relationship between the effectiveness and safety profile of seaweed extracts and their processing conditions and source material, recommendations of seaweed extract use should be adapted to local contexts. This involves taking account of the variations in seaweed species available in different regions, environmental factors that influence biomass quality, and the different needs for end use (e.g., food vs. fertilizer). If not, the use of seaweed products will continue to be patchy, especially if there is no extensive field testing done across different crops, seasons, and geographies, without specific guidance. To summarize, solutions to these challenges will involve developments in extraction technology (higher yield and consistency), better standardized extraction methods (product quality), increased investments in scalable extraction infrastructure (accessibility), full safety assessment (regulatory concerns), and more extensive field research focused on a range of extractions to produce location-specific usage guidelines (Ghelichi & Jacobsen, 2025; Cardoso *et al.*, 2025) ^[6, 5].

12. Future Perspectives

Seaweed-based biostimulants are emerging as important management tools in the future, climate-smart pulse management systems such as chickpea, which have the potential to boost nutrient-use efficiency, stress tolerance, and can be integrated in a low-chemical management. Recent reviews focus on the use of “tonic” to more specific, multiple, and crop-oriented applications. Other possibilities for future integration with precision agriculture involve the use of precision tools such as remote sensing, big data, and smart irrigation to optimize the timing, dose, and placement of seaweed in variable fields to enhance fertilizer use efficiency and resilience in resource-limited systems such as chickpea-based rotation. These are part of a larger concept of “sustainable intensive agriculture,” which aims at higher production from fewer inputs and in the face of climate stress (Boukhari *et al.*, 2020) ^[4]. The other important aspect is the development of improved formulations. Reviews showed an increase in the need for crop-specific and stress-specific products with improved control of the product composition (defined polysaccharide and hormone profiles), improved stability (solid- or controlled-release forms), and ideally for integration of macro /micronutrients to optimize the stress response under drought, salinity, and heat conditions (Rabhi *et al.*, 2025; Boukhari *et al.*, 2020) ^[4, 12]. Multiple papers highlight opportunities for complementing with biofertilizers and with organic inputs. In microbial inoculants and other biostimulants, the co-application and blending of seaweed products are suggested for leveraging their synergistic effects on the rhizosphere microbiome, nutrient cycling, and stress resilience (Ali *et al.*, 2021; Kapoore *et al.*, 2021; Raj *et al.*, 2022) ^[1, 8, 13]. These integrated packages can help enhance soil health and minimize the use of synthetic fertilizers for chickpea, where already symbiotic N fixation and sometimes organic manures are being applied. Seaweed biostimulants are presented in general as valuable tools for climate-resilient production systems, providing an increased performance and stability of crops when facing abiotic stress and contributing to sustainable and circular agriculture. They will need further field validation to be fully exploited for chickpea and recommendations, and their integration in precision and integrated nutrient management strategies will depend on Boukhari *et al.* (2020) ^[4] and Rabhi *et al.* (2025) ^[12].

13. Conclusion

Overall, seaweed extract has shown promising results as an eco-friendly biostimulant to enhance the growth, physiological performance, yield, and quality of chickpea (*Cicer arietinum* L.). The review underscores that application of seaweed extract in the seed treatment, foliar spraying, or soil application has shown improvement in seed germination, root development, photosynthetic efficiency, chlorophyll synthesis, nutrient uptake, nodulation, and overall productivity with a subsequent increase in pod formation and seed yield. The extracts from seaweed contain bioactive compounds like plant growth regulators, amino acids, vitamins, and micronutrients, which help to promote plant metabolism and tolerance to abiotic stresses like drought, salinity, heat stress, etc. Seaweed extract also enhances soil microbial activity, soil fertility, and reduces the need for synthetic fertilizers, which contributes to environmentally friendly cultivation of chickpeas. Its

relevance to pulse production is related to its ability to increase resource-use efficiency, crop resilience and returns, and to preserve ecological balance. The standardisation of extraction protocols, the optimization of doses and timing of seaweed-based biostimulants, and the combination of precision nutrient and water management with seaweed-based biostimulants are suggested for future research. These strategies will boost sustainable production systems for pulses and help to mitigate climate change and achieve long-term food and nutritional security in the country.

References

1. Ali O, Ramsubhag A, Jayaraman J. Biostimulant properties of seaweed extracts in plants: implications towards sustainable crop production. *Plants*. 2021;10(3):531. <https://doi.org/10.3390/plants10030531>
2. Arioli T, Mattner S, Islam M, Tran T, Weisser M, Winberg P, *et al.* Applications of seaweed extracts in agriculture: an Australian perspective. *Journal of Applied Phycology*. 2023;36:713–726. <https://doi.org/10.1007/s10811-023-03120-x>
3. Bhushan S, Veeragurunathan V, Bhagiya B, Krishnan S, Ghosh A, Mantri V. Biology, farming and applications of economically important red seaweed *Gracilaria edulis* (S. G. Gmelin) P. C. Silva: a concise review. *Journal of Applied Phycology*. 2023;35:983–996. <https://doi.org/10.1007/s10811-023-02955-8>
4. Boukhari M, Barakate M, Bouhia Y, Lyamlouli K. Trends in seaweed extract based biostimulants: manufacturing process and beneficial effect on soil-plant systems. *Plants*. 2020;9(3):359. <https://doi.org/10.3390/plants9030359>
5. Cardoso C, Matos J, Afonso C. Extraction of marine bioactive compounds from seaweed: coupling environmental concerns and high yields. *Marine Drugs*. 2025;23(9):366. <https://doi.org/10.3390/md23090366>
6. Ghelichi S, Jacobsen C. Seaweed proteins: properties, extraction, challenges, and prospects. *Journal of Food Science*. 2025;90(8):e70418. <https://doi.org/10.1111/1750-3841.70418>
7. Hnini M, Aurag J. Prevalence, diversity and applications potential of nodules endophytic bacteria: a systematic review. *Frontiers in Microbiology*. 2024;15:1386742. <https://doi.org/10.3389/fmicb.2024.1386742>
8. Kapoore R, Wood E, Llewellyn C. Algae biostimulants: a critical look at microalgal biostimulants for sustainable agricultural practices. *Biotechnology Advances*. 2021;49:107754. <https://doi.org/10.1016/j.biotechadv.2021.107754>
9. Kumari S, Sehrawat K, Phogat D, Sehrawat A, Chaudhary R, Sushkova S, *et al.* *Ascophyllum nodosum* (L.) Le Jolis, a pivotal biostimulant toward sustainable agriculture: a comprehensive review. *Agriculture*. 2023;13(6):1179. <https://doi.org/10.3390/agriculture13061179>
10. Mughunth R, Velmurugan S, Mohanalakshmi M, Vanitha K. A review of seaweed extract's potential as a biostimulant to enhance growth and mitigate stress in horticulture crops. *Scientia Horticulturae*. 2024;334:113312. <https://doi.org/10.1016/j.scienta.2024.113312>
11. Nakhate P, Van Der Meer Y. A systematic review on seaweed functionality: a sustainable bio-based material. *Sustainability*. 2021;13(11):6174. <https://doi.org/10.3390/su13116174>
12. Rabhi M, Derbak L, Bendif H, Boufahja F, Abu-Elsaoud A, Garzoli S. Seaweed-derived biostimulants for sustainable crop production: a review. *Journal of Biotechnology*. 2025;408:1–[end page]. <https://doi.org/10.1016/j.jbiotec.2025.09.013>
13. Raj Y, Ali N, Pati A, Kumar R. Cleaner production technologies for the amelioration of soil health, biomass and secondary metabolites in *Ocimum basilicum* L. under Indian Western Himalaya. *Frontiers in Plant Science*. 2022;13:976295. <https://doi.org/10.3389/fpls.2022.976295>
14. Sariñana-Aldaco O, Rivera-Solís L, Benavides-Mendoza A, Robledo-Olivo A, Rodríguez-Jasso R, González-Morales S. Using brown algae in the plant–soil system: a sustainable approach to improving the yield and quality of agricultural crops. *Horticulturae*. 2025;11(1):94. <https://doi.org/10.3390/horticulturae11010094>
15. Sujeeth N, Petrov V, Guinan K, Rasul F, O'Sullivan J, Gechev T. Current insights into the molecular mode of action of seaweed-based biostimulants and the sustainability of seaweeds as raw material resources. *International Journal of Molecular Sciences*. 2022;23(14):7654. <https://doi.org/10.3390/ijms23147654>
16. Vangenechten B, De Coninck B, Ceusters J. How to improve the potential of microalgal biostimulants for abiotic stress mitigation in plants? *Frontiers in Plant Science*. 2025;16:1568423. <https://doi.org/10.3389/fpls.2025.1568423>
17. Wazeer H, Gaonkar S, Doria E, Pagano A, Balestrazzi A, Macovei A. Plant-based biostimulants for seeds in the context of circular economy and sustainability. *Plants*. 2024;13(7):1004. <https://doi.org/10.3390/plants13071004>
18. Yasmeen A, Maharajan T, Rameshkumar R, Sindhamani S, Banumathi B, Prabakaran M, *et al.* Role of seaweeds for improving soil fertility and crop development to address global food insecurity. *Crops*. 2025;5(3):29. <https://doi.org/10.3390/crops5030029>