

Review Article

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Role of Seaweed Biostimulant in Plant Growth and Stress Resistance - A Review

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ABSTRACT

Modern agriculture must boost food production while reducing environmental harm. Traditional inputs like synthetic pesticides and fertilizers degrade soil and ecosystems. Plant biostimulants, especially those from seaweed, offer a sustainable alternative by enhancing natural plant functions. Rich in phytohormones, polysaccharides, amino acids, and minerals, seaweed extracts improve growth, photosynthesis, and nutrient uptake. Brown Seaweed Extract (BSE) acts as a synergistic potent biostimulant in vegetable cropping systems, for physiological enhancements and improved yields that stimulate root and shoot development, improve nutrient and water uptake, and enhance photosynthetic efficiency, collectively strengthening plant metabolism and stress resilience, withstanding fluctuations in water availability, temperature, and salinity. Its effects include enhanced root growth and nutrient uptake, allowing vegetables to better utilize soil resources and potentially reduce dependence on synthetic fertilizers. They also strengthen plant defenses against abiotic stresses (drought, salinity, heat) and biotic threats (pests, diseases) by activating antioxidants, stress proteins, and systemic resistance. BSE-induced hormonal and metabolic priming improves the growth base, particularly in early phases. Crucially, it provides improved stress tolerance against climatic variables like drought, temperature extremes, and salinity, making it valuable under increasing climatic variability. Their multifaceted benefits make seaweed biostimulants a promising eco-friendly tool for resilient agriculture. This article reviews the need for continued research into their modes of action and standardized application protocols to fully harness their potential in creating more resilient and productive agricultural systems.

Keywords

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Introduction

Biostimulants, such as those derived from seaweed, have become essential tools in contemporary agriculture for enhancing crop growth, stress resistance, and soil health.

In the review of earlier works on impact of *Ecklonia maxima* extract on growth and yield of tomato (*Solanum lycopersicum* L.), focusing on key areas like general usage of biostimulants, physiological effects of seaweed extracts, mechanisms of action, comparative

effectiveness, and current research gaps has been critically examined and narrated.

Sectional seaweed extracts are notably significant due to their multiple functions in encouraging plant growth. The popularity of these seaweed-based products is attributed to their active compounds, including phytohormones, amino acids, vitamins, and polysaccharides, which affect plant physiological and biochemical processes. These biostimulants play a vital role in boosting the growth, development, and overall performance of crops from the nightshade family. Biostimulants, being substances or microorganisms that stimulate plant growth and improve plant health, are valuable instruments for sustainable agriculture (Chaudhari *et al.*, 2023). Among seaweeds, *Ecklonia maxima*, Family: Lessoniaceae, is a species of kelp native to the South African Atlantic coast, and is commonly employed in horticulture due to its growth-promoting properties akin to auxins and cytokinins and it is commonly known as sea bamboo and is a type of brown macro algae. Studies demonstrate that seaweed extracts can improve crop growth and yield indices. While these extracts improve flowering in plants, the processes underlying this phenomenon are still not thoroughly understood (Dookie *et al.*, 2021). In the current study, brown seaweed extracts from *A. nodosum* and *Sargassum* sp. were applied to tomato plants, leading to significant increases in flower buds, flowers, and fruits. The use of low amounts of commercial Kelp extract (*Ecklonia maxima*: Kelpak) added to fertilizer is advantageous in both agriculture and horticulture. Kelpak promotes roots in field crops, increases yields, and offers additional benefits, such as pest reduction. Its efficacy is largely attributed to its cold-process production and high auxin/low cytokinin ratio (Robertson-Andersson *et al.*, 2006).

Kelp is a big, brown algae plant that grows in the sea. It has long, strong stems and a wide, leaf-like part called a frond, which is split into narrow strips.

Role of biostimulants in Horticulture

Plant biostimulants are substances or microbes that boost nutrient use, stress tolerance, and crop quality, independent of nutrient content. They include biofertilizers and beneficial microbes like rhizobium and mycorrhizae. Clear definitions help distinguish them from fertilizers or pesticides and support regulatory acceptance (Du Jardin, 2015). According to Yakhin *et al.*, (2017) plant biostimulants, derived from diverse

biological sources, enhance productivity through complex interactions, and their validation should focus on efficacy and broad mechanisms, not specific actions. Modern agriculture seeks sustainable practices that maintain yield and quality with fewer inputs. Biostimulants, rich in bioactive compounds, enhance nutrient efficiency and stress tolerance, improving growth, quality, and pigment content in vegetables (Bulgari *et al.*, 2015). Climate change, driven partly by excessive agricultural inputs, demands more sustainable practices to meet future food needs. Biostimulants such as seaweed extracts offers eco-friendly solutions by enhancing plant growth, stress resistance, and crop quality. According to Cristofano *et al.*, (2021) their origins, effects on hormonal and physiological pathways, and their proven benefits in major vegetable groups like cucurbits, leafy greens, and nightshades—supporting their relevance in sustainable tomato cultivation under *Ecklonia maxima* application. Calvo *et al.*, (2014) observed that plant biostimulants can be applied through foliar spray, soil drenching, or seed treatment, each offering unique benefits. Foliar sprays enable rapid nutrient absorption through leaves; soil drenches enhance root development and microbial activity, while seed treatments boost germination and early vigour. The choice of method depends on crop type, growth stage, and biostimulant used to maximize effectiveness. Seaweed extracts from *Ascophyllum nodosum* and *Sargassum* species have been shown to significantly enhance flowering and fruiting in tomato plants. This study revealed that foliar application of these extracts increased the expression of six key flowering genes (SFT, SP, J, AN, FA, CO). These findings suggest a molecular basis for the improved flowering observed, supporting the sustainable use of seaweed extracts as biostimulants in horticulture (Dookie *et al.*, 2021). The influence of *Ecklonia maxima* extract (Kelpak SL) on hybrid alfalfa nutrient profiles improved increased levels of phosphorus, potassium, zinc, and manganese in plant tissue, although calcium, magnesium, copper, and molybdenum remained stable. These changes led to a more favorable nutrient balance, particularly by lowering the Ca: P ratio and raising the K: (Ca+Mg) ratio (Sosnowski *et al.*, 2014). A greenhouse experiment tested foliar applications of *Macrocystis integrifolia* and *Ecklonia maxima* extracts on beans grown under different moisture regimes. Both acted as growth regulators, influencing shoot/root ratios, leaf area, and node formation, with responses depending on soil moisture levels. A bioassay using soybean callus indicated that cytokinin-like compounds and growth

inhibitors were present but degraded more quickly than growth-promoting elements upon dilution (Temple *et al.*, 1989).

Role of seaweed extracts in plant growth and development

Seaweed extracts, particularly from brown algae such as *Ecklonia maxima*, have garnered significant attention in recent decades for their role as natural plant biostimulants in enhancing plant growth and development. These extracts are rich in bioactive compounds including phytohormones (auxins, cytokinin, gibberellins), amino acids, vitamins, polysaccharides (e.g., alginates, laminarins, and fucoidans), and trace elements that contribute to improved physiological and biochemical processes in plants (Khan *et al.*, 2009; Craigie, 2011). Ovalle *et al.*, (2017) evaluated the use of *Ecklonia maxima* seaweed extract (Kelpak®) to improve fruit set and retention in 'Bing' cherry trees for three years, both autumn (postharvest) and spring applications significantly enhanced fruit set, yield, and flower starch content. The most effective results came from two 0.3% Kelpak sprays applied at 110 and 120 days after harvest, suggesting that Kelpak can be a promising tool to boost cherry production. Moreover, seaweed extracts improve chlorophyll content, delay senescence, and promote photosynthetic efficiency, contributing to enhanced plant biomass and yield (Spinelli *et al.*, 2010; Jannin *et al.*, 2013). In addition to promoting vegetative growth, seaweed extracts enhance nutrient uptake by chelating minerals and stimulating root architecture, which increases the plant's capacity to absorb macro- and micronutrients (Rathore *et al.*, 2009; Mancuso *et al.*, 2006). The improvement in nutrient use efficiency also allows for a reduction in synthetic fertilizer usage, making seaweed-based biostimulants a sustainable solution in modern agriculture. Furthermore, seaweed extracts have been associated with increased tolerance to abiotic stresses such as drought, salinity, and temperature extremes. This stress mitigation is attributed to the stimulation of antioxidant activity, proline accumulation, and regulation of stress-responsive genes (Nair *et al.*, 2012; Rayirath *et al.*, 2009). Rouphael and Colla (2020) demonstrated that biostimulants containing amino acids and other protein hydrolysates significantly improve plant growth and stress tolerance. Recent transcriptomic studies have confirmed that seaweed extracts can modulate the expression of genes involved in photosynthesis, carbon and nitrogen metabolism, and stress response (Jannin *et al.*, 2013; Wally *et al.*, 2013).

Effect of seaweed-based biostimulants on vegetable crops

Ecklonia maxima-based seaweed concentrate (SWC) has been reported (Crouch & Van Staden, 1992) to enhance tomato seedling growth when applied as a soil drench, while foliar application was ineffective at early stages. However, at later stages, foliar application of SWC promoted early fruit ripening increased total fruit weight by 17%, and improved fruit number by around 10%, suggesting that both the method and timing of application influence its effectiveness. Ali *et al.*, (2021) reported that seaweed extracts enhance plant growth, yield, and stress resistance through their bioactive compounds. They stimulate plant defenses, influence hormones, and support beneficial soil microbes. Whole extracts are more effective than individual components due to their complex interactions. Being organic and compatible with other inputs, seaweed products are valuable for sustainable and integrated crop management systems. Javaria *et al.*, (2016) study evaluated the effects of different nutrient sources—bio-fertilizers (effective microorganisms), farmyard manure, and NPK—on tomato quality. Seven treatments were tested in a pot experiment. Results showed that combining bio-fertilizers with farmyard manure significantly improved physicochemical traits, sensory qualities, and shelf life of tomatoes compared to NPK. This is the first study to examine how effective microorganisms affect taste-active components and their link to quality and shelf life, offering valuable data for future research.

This study examined the effects of seaweed extract (*Nizamuddiniana zanardinii*), silicon, and selenium on tomato quality and yield in palm peat + perlite and coco peat + perlite substrates. Seaweed extracts enhanced carbohydrate content, TSS, pH, and yield. Seaweed extract and application of selenium improved fruit firmness, volume, and yield, especially with palm peat. The findings highlight the benefits of seaweed and silicon sprays and support palm peat as a viable hydroponic substrate (Jalali *et al.*, 2022). The excessive use of chemical fertilizers in greenhouse tomato farming has hindered productivity. A greenhouse study in Shandong, China tested a seaweed extract from *Sargassum horneri* (SES) at varying doses (0, 30, 60, 90 kg/ha) and found that SES significantly improved tomato yield (by 4.6–6.9%), fruit firmness, and net returns. The optimal dose was 60 kg/ha, which enhanced photosynthesis, shortened ripening time, and aligned harvest with peak market prices (Yao *et al.*, 2020).

Hussain *et al.*, in 2021, evaluated polyamine (PA) levels in *Ecklonia maxima* and its seaweed concentrate, Kelpak. Samples of stipe-stalks, fronds, and Kelpak on monthly-basis were collected over two years. Putrescine and spermine across plant parts and Kelpak was registered at varying concentrations Using HPLC, while spermidine was undetectable confirming the presence of biologically active PAs in *E.maxima* and Kelpak, as well as regular growth hormones like auxins and cytokinin, supporting their role in plant growth stimulation. They analyzed seaweed extract (SWE), in addition, from *Durvillaea potatorum* and *Ascophyllum nodosum* on tomato plants and soil. SWE improved plant growth, yield, and quality while enhancing soil health by boosting bacterial count, nitrogen availability, and beneficial microbial diversity, supporting sustainable agriculture through improved plant performance and enhanced soil ecosystem function. Foliar application of aqueous seaweed extracts significantly increased potato yields, especially in the King Edward variety. Similar yield increases were noted with the synthetic cytokinin kinetin, indicating that the seaweed extract's effectiveness was likely due to its cytokinin content as reported from trials done during 1974 -75. The main yield increase was in marketable ware potatoes (Blunden and Wildgoose, 1977). The application of seaweed extracts through foliar spray or soil drenching has shown marked improvements in seed germination, root initiation, shoot elongation, and flowering in several crops, including tomato (*Solanum lycopersicum*), due to their hormone-like activity. Auxins and cytokinins present in seaweed extracts have been reported to enhance cell division and elongation, leading to improved root and shoot growth (Zodape *et al.*, 2011; Crouch & van Staden, 1993). A 2010 field trial evaluated the seaweed extract "Primo" on potato (cv. Sante) through foliar sprays at different growth stages. Seaweed application appreciably improved plant growth, tuber yield, and quality, the highest yield being achieved with sprays at 30 and 60 days after planting. Treated tubers also showed increased nitrogen, total soluble solids, and protein content, confirming effectiveness of the extracts (Haider *et al.*, 2012). A study under cool, long-day conditions found that foliar application of seaweed extract had no significant effect on potato growth or yield. Minor, non-significant benefits were observed when applied three weeks after emergence, before tuber initiation (Kuisma, 1989). A field study on potato cv. 'Spunta' showed that algae extract (200 mg/L) significantly enhanced plant growth, yield, and tuber quality. The combined soaking and spraying treatment gave the highest dry matter (19.4%) and starch (13.3%)

content. Seaweed extracts (20–40%) significantly enhanced in vitro germination, shoot and root development in brinjal tissue culture. The findings support SLEs as effective, natural alternatives to synthetic plant hormones for mass propagation (Satish *et al.*, 2015). A field study in Iraq showed that daily drip irrigation combined with 4 ml/L seaweed extract foliar spray significantly enhanced vegetative growth and yield of Barcelona eggplant. This treatment outperformed all others, highlighting the effectiveness of integrating optimal irrigation with natural biostimulants (Al-Bayati *et al.*, 2020). Laboratory trials showed that *Sargassum wightii* extract significantly enhanced brinjal growth, chlorophyll content, and fruit yield compared to control and red seaweed extract. It also improved biochemical composition, indicating its potential as an effective organic fertilizer that boosts yield and maintains soil health (Sreelatha *et al.*, 2018).

In eggplant (cv. Paris) seaweed extract @ 1 ml/L significantly improved vegetative and yield traits. The best overall performance was observed with the combination of 1 ml/L seaweed extract and the Barshelona cultivar. Yusuf *et al.*, (2021) examined the impact of different seaweed extracts and NPK combinations on the vegetative growth of chili plants using seven treatments in a randomized block design. Treatments included extracts from *Ulva* sp., *Caulerpa* sp., and *Sargassum* sp., applied alone or with NPK. Among all, *Ulva* sp. extract alone (T1) significantly improved growth parameters. The results suggest its potential as an effective organic fertilizer. The impact of True-Algae-Max (TAM®), a seaweed-based biostimulant, on the growth, yield, and antioxidant properties of *Capsicum annuum* under greenhouse conditions over two seasons. Foliar application of TAM®, especially at 0.5%, significantly boosted yield, chlorophyll, and antioxidant compounds compared to traditional NPK fertilizers. TAM® also showed strong antioxidant activity and DPPH inhibition. Results support TAM® as a sustainable alternative to chemical fertilizers in agriculture (Ashour *et al.*, 2021).

The impact of different application rates of Wokozim, a seaweed-based biostimulant from *Ascophyllum nodosum*, on chilli (*Capsicum annuum*) growth and yield under protected conditions improved yield. Four treatments (0–15 g/plant) were tested, with T4 (15 g/plant) showing the highest improvements in plant height, leaf count, pod number, pod weight, and pod length. Statistical analysis confirmed significant differences compared to control.

Thus, T4 is recommended for optimal chili cultivation performance (Sampath *et al.*, 2025).

Fatimah and Daud (2018) assessed the effects of four solvent-based seaweed extracts at varying concentrations on the in vitro seed germination of tomato (*Lycopersicon esculentum*) and chilli (*Capsicum annuum*) and reported that the optimal concentration for tomato seedling growth was at 2.50 mg/L, with dichloromethane (DCM) extract showing the best results. For chilli, hexane extract of *Sargassum* sp. was most effective. Phytochemical analysis revealed alkaloids and terpenoids as dominant compounds in all extracts.

The use of liquid seaweed extracts from *Kappaphycus alvarezii* (K-sap) and *Gracilaria edulis* (G-sap) as seed priming agents was explored for *Capsicum frutescens*. Seed priming with seaweed in chilli at various concentrations and durations, significantly improved seed germination, seedling vigour, physiological and biochemical traits. Morphological and reproductive traits also showed notable enhancement. Principal component analysis (PCA) helped identify effective priming treatments, with several K-sap and G-sap combinations recommended for better germination, storability, and yield in chili cultivation (Dutta *et al.*, 2019). Vijayakumar *et al.*, in 2019 too, tried almost a similar study to evaluate the impact of seaweed liquid fertilizer (SLF) from *Codium decorticans* on *Capsicum annuum* under lab and pot conditions. Seeds treated with various SLF concentrations (10–50%) showed improved growth parameters. The 20% SLF concentration yielded the highest germination rate, biomass, shoot and root growth, leaf area, and biochemical content. Results indicate that *C. decorticans* SLF is a promising, eco-friendly, and cost-effective biofertilizer for chilli cultivation.

The effects of individual and combined applications of seaweed liquid fertilizers (SLF) and recommended chemical fertilizers (RCF) on *Capsicum annuum* was studied by Jayasinghe *et al.*, (2016). The best results in shoot height (15 cm) and dry weight (0.856 g) were recorded with 75% SLF plus RCF, especially from *Sargassum wightii* and *Kappaphycus alvarezii*. Combined SLF+RCF treatments significantly improved growth traits like root weight, leaf number, flower and pod count, and pod length compared to SLF or RCF alone. Thus, integrating 75% SLF with RCF is more effective than using SLF alone in enhancing chili crop growth and yield. Results of evaluation of the effects of seaweed extract (SE), fertilizers (FF), and their

combination (SE+FF) on sweet pepper grown in greenhouse conditions, showed that SE and SE+FF significantly increased the number of fruits, fruit weight, and overall yield compared to FF and the control. SE alone offered the best yield at the lowest cost. However, no major differences were observed in vegetative growth traits among treatments. Therefore, SE is recommended for enhancing sweet pepper productivity efficiently (Salazar-Salazar *et al.*, 2022). A study investigating the combined application of *Ecklonia maxima* seaweed extract (SE) and different concentrations of molybdenum (Mo) in spinach cultivation under protected conditions revealed significant improvements. SE notably boosted fresh head weight, ascorbic acid, polyphenol levels, and essential nutrients such as nitrogen, phosphorus, potassium, and magnesium. Mo supplementation further enhanced plant height, stem thickness, carotenoid content, and nitrogen use efficiency. The optimal response was observed when SE was combined with 4–8 $\mu\text{mol L}^{-1}$ Mo, resulting in increased leaf count, dry matter content, and Mo accumulation, leading to improved spinach yield and nutritional value (La Bella *et al.*, 2021).

Alkaline extracts from five Caribbean seaweeds, used as seed bio-primers of tomato and sweet pepper improved germination, seedling vigour, chlorophyll, and carotenoid levels. Foliar sprays reduced early blight and bacterial spot incidences while significantly increasing fruit yield. Though extracts showed no direct antimicrobial action, they enhanced plant defense enzymes and gene expression linked to immunity, suggesting strong elicitor activity. The findings support seaweed extracts as sustainable biostimulants in crop production and disease resistance (Ali *et al.*, 2023).

The impact of *Ecklonia maxima* extract on melon, cucumber, and tomato was evaluated in a study by Lefi *et al.*, (2023). A lower dose (C1) enhanced photosynthetic efficiency and chlorophyll concentration, particularly in melon. In contrast, a higher dose (C2) led to greater shoot biomass across all three crops. Cucumber plants showed more vigorous vegetative growth, while tomato plants experienced modest improvements in root development and photosynthetic activity. The effectiveness of the treatments did vary by crops and concentrations.

Salt stress, particularly from NaCl, can negatively impact zucchini by impairing photosynthesis, nutrient uptake, and leaf structure. However, foliar application of *Ecklonia maxima* seaweed extract (SWE) every two

weeks under these conditions led to improved shoot biomass, yield, chlorophyll content, and CO₂ assimilation. SWE-treated plants also maintained a more favorable potassium-to-sodium ratio and exhibited anatomical adaptations such as smaller stomata. Meanwhile, untreated plants showed higher accumulation of phenolics in leaves (Rouphael *et al.*, 2017).

In hydroponic systems, *Ecklonia maxima*-based biostimulants like Basfoliar Kelp (applied at 0–4 mL L⁻¹) significantly benefited leaf lettuce. At 2–4 mL L⁻¹, treatments enhanced plant growth, yield, biomass accumulation, stomatal conductance, and nutrient use efficiency. The 2 mL L⁻¹ dose was particularly effective in delaying leaf senescence and extending shelf life up to 21 days, maintaining the produce's commercial quality (Miceli *et al.*, 2021).

Foliar sprays of kelp extracts from *Macrocystis integrifolia* and *Ecklonia maxima* improved bean (*Phaseolus vulgaris*) yields by about 24% on average. Extracts containing plant hormones such as auxins, cytokinins, and gibberellins also boosted yields, though not as effectively as the full kelp concentrates as confirmed by extract bioassay (Temple and Bomke, 1989).

With increasing consumer demand for leafy vegetables, excessive nitrogen fertilization has led to harmful nitrate accumulation in leaves. A greenhouse study examined the use of *Ecklonia maxima* extract and a legume-derived protein hydrolysate on baby lettuce under nitrogen levels of 0, 10, and 20 kg/ha. Both biostimulants improved yield, leaf area, antioxidant levels, and pigment concentration, especially at 10 kg N/ha, helping reduce the need for higher nitrogen inputs. While nitrate content rose with more nitrogen, levels remained within safe limits in *E. maxima*-treated plants, indicating improved nitrogen efficiency and safety (Di Mola *et al.*, 2020). Lastly, a two-year field study in Poland investigated the effect of *Ecklonia maxima* extract (Kelpak SL) on the yield and seed quality of two bean varieties, Aura and Toska. Foliar applications at 0.2% and 0.4%—either once or twice—enhanced yields without negatively impacting starch, sugar, or protein content. In particular, anthocyanin and phenolic content increased, especially in double-treated Toska plants, while antioxidant properties improved in Aura. The study concluded that Kelpak SL is a safe and environmentally friendly option for enhancing bean yield and quality (Kocira *et al.*, 2018).

Stress resistance

Interest in plant biostimulants for vegetable cultivation is rapidly increasing due to their demonstrated benefits in improving both yield and product quality. Recent findings highlight their potential as sustainable and economical solutions for enhancing the performance of greenhouse-grown vegetables by promoting growth, improving quality, and increasing resilience to stress. Compounds such as protein hydrolysates and seaweed extracts, particularly from *Ascophyllum nodosum* and *Ecklonia maxima*, have shown notable effectiveness, especially under environmental stress. (Petropoulos, 2020).

Under drought stress, greenhouse-grown chicory responded positively to *Ecklonia maxima*-derived seaweed extract (SWE). Applications improved plant hydration status, yield, uptake of key nutrients (P, K, Ca, Mg), chlorophyll content, and accumulation of protective compounds like proline and polyphenols. Additionally, SWE enhanced water and nitrogen use efficiency, helping maintain both quality and productivity under challenging moisture conditions (Sabatino *et al.*, 2023).

Moncada *et al.*, (2022) reported that a commercial biostimulant based on *E. maxima* extract was employed to provide natural auxin, while 1-naphthaleneacetic acid (NAA) was used to produce synthetic auxin. The control group consisted of seedlings that were just given water. Tomato seedlings treated with 100 µg L⁻¹ of natural auxins from *E. maxima* extract resulted in taller plants (+22%), more leaf number (+12%), larger leaf area (+44%), and stronger stems (+12%). The biostimulant derived from *E. maxima* extracts outperformed the synthetic source of auxins, NAA, in terms of seedling quality, shoot and root growth. This is further supported by Sharma *et al.*, (2023), who concluded that the complex composition of natural seaweed extracts often leads to superior growth promotion and stress resistance compared to single-compound synthetic alternatives. Righini *et al.*, (2023) found that natural seed treatments, such as water-soluble polysaccharides (WSPs) from *Ecklonia maxima*, provide environmentally benign alternatives to chemicals. This study found that WSPs improved tomato seedling growth and induced resistance to Fusarium wilt for 46 days, as evidenced by biochemical changes and increased defense related compounds and gene expression. In the study of Ngala *et al.*, (2016) two seaweed extracts (*Ascophyllum nodosum* and *Ecklonia maxima*) were evaluated against root-knot

nematodes *Meloidogyne chitwoodi* and *M. hapla* as a result he found that altered hatching, attraction, and infectivity in vitro, however the effects in vivo were less obvious due to probable dilution during application. Righini *et al.*, (2021) provide an overview of due to constraints on synthetic pesticides, in this study looked into merineous extracts from *Anabaena minutissima*, *Ecklonia maxima*, and *Jania adhaerens* for controlling *Rhizoctonia solani* in tomatoes. It is found that treatment boosted germination, development, and plant resistancy, indicating potential as eco-friendly biocontrol agents. This aligns with recent research by Deleu *et al.*, (2023), who found that seaweed-derived compounds can enhance the expression of genes associated with plant defense, making them more resilient to soil-borne pathogens. Crouch *et al.*, (1993) had shown that applying seaweed concentrate (SWC), (*Ecklonia maxima*), as a soil drenching substance to tomato seedlings considerably boosted plant development and decreased *Meloidogyne incognita* infection. The suppressive effect on nematode infestation was lessened by ashing SWC. SWC reduced the infection of root-knot nematodes on removed roots of a tomato cultivar that was vulnerable in an in vitro experiment. Application of the same amounts of SWC to a nematode-resistant cultivar enhanced the quantity of egg masses.

Kelpak provides a multifaceted, nature inspired strategy to bolster crops against increasingly unpredictable climates. It primes physiological defenses, supports growth and recovery, and strengthens metabolic resilience.

Physiology of improved vegetable yield by brown seaweed extract

Seaweed extracts, also known as liquid seaweed fertilizers, can positively impact plant growth and development. They act as biostimulants, containing natural plant growth regulators and other beneficial compounds that enhance various plant processes. Studies indicate that seaweed extracts can increase crop yields, improve nutrient uptake, and enhance stress resistance in plants.

Enhanced photosynthesis

Application of brown seaweed extract (BSE) has been reported to enhance photosynthetic efficiency in plants through multiple physiological and biochemical

mechanisms. The bioactive components of BSE, particularly cytokinins and essential trace minerals such as magnesium (Mg) and iron (Fe), play a vital role in improving chlorophyll synthesis and photosystem activity, thereby increasing chlorophyll content and stomatal conductance (Khan *et al.*, 2009; Craigie, 2011). Cytokinin-like compounds present in BSE are known to delay leaf senescence and promote chloroplast development, which sustains photosynthetic performance over a longer growth period (Zhang & Ervin, 2008). Enhanced photosynthetic capacity leads to greater carbohydrate assimilation, which supports vegetative growth, flowering, and fruit development, ultimately contributing to increased biomass accumulation and higher yield (Battacharyya *et al.*, 2015; Arioli *et al.*, 2015). Experimental studies on *Solanum lycopersicum* (tomato) have demonstrated that foliar application of BSE significantly increased chlorophyll concentration and net photosynthetic rate compared to untreated controls, resulting in improved plant vigor and fruit yield (Kumar *et al.*, 2020; Ali *et al.*, 2021). Overall, these findings suggest that BSE acts as an effective biostimulant by promoting enhanced photosynthetic performance and yield potential in crops.

Improved root development and nutrient uptake

Improved root development and nutrient uptake are among the most significant physiological effects induced by the application of seaweed-based biostimulants (BSEs). These biostimulants are known to contain naturally occurring plant growth regulators, particularly auxin-like and cytokinin-like compounds, which play crucial roles in promoting root elongation and the formation of lateral roots (Khan *et al.*, 2009; Craigie, 2011). The enhanced root system resulting from BSE treatment increases the total root surface area, thereby improving the plant's capacity to absorb water and essential nutrients from the soil (Sharma *et al.*, 2014). This improvement in below-ground architecture translates directly into above-ground productivity, as plants with well-developed and branched root systems exhibit greater vigor, leading to improved nutrient translocation and higher fruit yield (Kocira *et al.*, 2020). Several studies have demonstrated that BSE application significantly enhances the uptake of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), as well as micronutrients including zinc (Zn), iron (Fe), and manganese (Mn) (Fan *et al.*, 2013; Ali *et al.*, 2021). Thus, by promoting root proliferation and facilitating

efficient nutrient absorption, seaweed-based biostimulants contribute substantially to improved plant growth and yield performance under both optimal and stress conditions.

Hormonal balance and fruit set

The application of seaweed-based extracts (BSE) has been found to play a significant role in maintaining hormonal balance and enhancing fruit set in various crops. These extracts are rich sources of naturally occurring phytohormones, particularly cytokinins, gibberellins, and auxins, which collectively regulate flowering, fruit initiation, and development processes. The presence of these bioactive compounds influences several physiological mechanisms that promote reproductive success, including enhanced floral differentiation, pollen viability, and ovule fertilization efficiency (Khan *et al.*, 2009; Sharma *et al.*, 2019). A balanced hormonal interaction is crucial for successful fruit set and retention. The cytokinins present in BSE are known to promote cell division and delay senescence, thereby sustaining floral organ vitality during the reproductive phase (Stirk *et al.*, 2003). Gibberellins, on the other hand, facilitate flower initiation and fruit growth by stimulating cell elongation and carbohydrate mobilization, while auxins such as indole-3-acetic acid (IAA) are involved in ovary development and fruit enlargement (Crouch & van Staden, 1993). The synergistic effect of these hormones contributes to improved flower initiation and reduced abscission of flowers and young fruits, ultimately enhancing the overall fruit set and yield (Zodape *et al.*, 2011). Empirical studies have demonstrated that plants treated with seaweed extracts exhibit significantly elevated endogenous levels of IAA and cytokinins during critical growth and reproductive stages. Such hormonal profiling indicates that BSE application enhances the hormonal equilibrium required for optimal reproductive development and yield improvement (Craigie, 2011). The result is a marked increase in the number of marketable fruits per plant, confirming the efficacy of seaweed-derived biostimulants in improving both fruit set and yield quality parameters.

Abiotic and biotic stress tolerance

Abiotic and biotic stress tolerance is one of the major physiological responses enhanced by the application of seaweed-based biostimulants (BSEs). The mechanism underlying this tolerance primarily involves the induction

of systemic acquired resistance (SAR) and the priming of antioxidant defense systems in plants. Bioactive compounds such as laminarin, mannitol, and betaines present in seaweed extracts play a key role in modulating stress-responsive signaling pathways and enhancing the activity of antioxidant enzymes, including superoxide dismutase, catalase, and peroxidase (Khan *et al.*, 2009; Shukla *et al.*, 2019). Through these biochemical adjustments, plants treated with BSEs exhibit improved resilience to abiotic stresses such as drought, salinity, and extreme temperatures, as well as biotic challenges caused by pathogens and pests. Furthermore, the maintenance of redox homeostasis and osmotic balance under stress conditions enables plants to sustain physiological functions and photosynthetic efficiency, thereby minimizing yield losses. For instance, in tomato plants subjected to drought stress, BSE application significantly reduced oxidative stress markers such as hydrogen peroxide (H₂O₂) and lipid peroxidation levels, indicating an enhanced antioxidant defense response (Goñi *et al.*, 2018). Consequently, these treated plants maintained higher fruit yield and quality compared to untreated controls, demonstrating the agronomic relevance of seaweed extracts in promoting stress tolerance and stabilizing productivity under adverse environmental conditions.

Stimulation of soil microbiome

The stimulation of the soil microbiome by seaweed-based biostimulants (BSEs) represents a key mechanism through which these natural products enhance crop performance. The organic compounds present in seaweed extracts, including polysaccharides, phenolics, amino acids, and betaines, act as prebiotic substrates that promote the proliferation and activity of beneficial rhizosphere microorganisms such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi (Khan *et al.*, 2009; Craigie, 2011). These microbial communities play an essential role in maintaining soil health by facilitating nutrient mineralization, enhancing nutrient uptake efficiency, and producing phytohormones that stimulate root development (Battacharyya and Prithiviraj, 2015). The improvement in soil microbiota composition and function ultimately contributes to enhanced plant growth and yield. A well-balanced and active microbial population supports nutrient cycling and organic matter decomposition, creating a more favorable rhizospheric environment for root proliferation and nutrient acquisition (Tandon *et al.*, 2022). Consequently, plants grown in soils treated with BSEs exhibit improved

root vigor, greater stress tolerance, and higher productivity compared to untreated controls. Empirical evidence supports these observations. In tomato (*Solanum lycopersicum*), for instance, the application of seaweed extracts has been reported to significantly increase microbial biomass and enzymatic activity in the rhizosphere, particularly those related to carbon and nitrogen cycling processes (Sangha *et al.*, 2015; Rouphael and Colla, 2020). Such microbial stimulation has been linked with improved plant nutrient status and yield performance, underscoring the indirect but crucial role of soil microbiome enhancement in the biostimulant efficacy of seaweed extracts.

Improved fruit quality and maturity

Improved fruit quality and maturity are among the most consistent and significant outcomes of applying seaweed-based biostimulants (BSEs) in Solanaceous crops such as tomato (*Solanum lycopersicum* L.). The underlying mechanisms involve the modulation of physiological and biochemical processes that govern fruit development. Seaweed extracts have been reported to influence sugar accumulation, cell wall-modifying enzymes, and pigment biosynthesis pathways, thereby enhancing the ripening process and overall fruit quality (Kumar *et al.*, 2020; Khan *et al.*, 2009). These bioactive compounds, including alginates, betaines, cytokinins, and auxins, interact with the plant's hormonal balance, resulting in improved carbohydrate metabolism and enhanced translocation of assimilates toward developing fruits (Craigie, 2011). Beyond increasing yield quantity, the application of BSEs enhances the qualitative attributes of fruits. Treated tomato plants often produce fruits that are larger, sweeter, and more uniformly ripened compared to untreated controls (Rathore *et al.*, 2009). Such improvements are commonly reflected in higher °Brix values (a measure of soluble sugar content), elevated lycopene concentrations, and superior firmness—traits directly associated with better taste, nutritional value, and shelf life (Zodape *et al.*, 2011). The enhanced lycopene synthesis in particular is attributed to the activation of pigment biosynthesis pathways under the influence of bioactive metabolites present in seaweed extracts (Khan *et al.*, 2009). Furthermore, seaweed extract application as a seed treatment has shown promise in improving early crop establishment. Soaking seeds in seaweed extract solutions has been observed to promote faster and more uniform germination, likely due to the presence of natural growth-promoting substances that stimulate early seedling vigor and enzymatic activity (Crouch and van

Staden, 1993). This early enhancement in seedling development contributes to uniform plant growth and ultimately supports better fruit set and maturity.

Role of seaweed extracts as biostimulants in enhancing plant growth and yield

Seaweed extracts (SWEs), commonly applied as liquid biofertilizers, function as biostimulants due to their rich content of naturally occurring plant growth regulators and bioactive compounds. Extensive research has demonstrated their efficacy in improving crop performance by enhancing physiological processes, nutrient acquisition, and resilience to stress.

Enhancement of photosynthesis

Seaweed extracts (SWEs) enhance photosynthetic efficiency in plants through mechanisms involving increased chlorophyll content and improved stomatal conductance, primarily attributed to their cytokinin content and micronutrients such as magnesium and iron (Battacharyya *et al.*, 2015; Crouch and van Staden, 1993). These bioactive compounds stimulate chloroplast biogenesis and protect photosynthetic machinery from oxidative stress, thereby elevating the rate of CO₂ assimilation and carbohydrate synthesis (Khan *et al.*, 2009). The resulting increase in photosynthate availability supports accelerated vegetative growth, earlier flowering, and enhanced fruit development, contributing to overall yield improvement. Empirical evidence from controlled foliar applications on tomato (*Solanum lycopersicum* L.) demonstrates significant elevations in total chlorophyll concentration (up to 28%) and net photosynthetic rate (Pn) compared to untreated controls, with corresponding gains in biomass accumulation and fruit quality parameters (Ali *et al.*, 2021; Spinelli *et al.*, 2010).

Improved root architecture and nutrient uptake

Seaweed extracts (SWEs) enhance root architecture and nutrient uptake primarily through compounds exhibiting auxin- and cytokinin-like activity, which stimulate root elongation and promote lateral root proliferation (Khan *et al.*, 2009; Crouch and van Staden, 1993). This hormonal modulation results in a more extensive and branched root system, thereby increasing the soil volume explored and improving the efficiency of water and nutrient absorption (Battacharyya *et al.*, 2015).

Table.1 Role of Kelpak in enhancement of crop resilience to stress

Mechanism	combating climate stresses
Stress tolerance	Mitigates drought, flooding, salinity, frost, shock
Root & shoot growth	Enhances water/mineral uptake, anchorage
Photosynthesis & yield	Improves energy conversion, fruit set, harvest quality
Salinity buffer	Restores growth and reduces oxidative damage under salt stress
Metabolic adaptation	Activates biochemical pathways for stress resilience
Yield & nutrition	Boosts productivity and crop quality under adverse conditions

[Sagoni *et al.*, 2024]

Consequently, plants treated with SWEs display enhanced uptake of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), as well as micronutrients including iron (Fe), zinc (Zn), and manganese (Mn) (Rathore *et al.*, 2009). These physiological improvements contribute to overall plant vigor, higher biomass accumulation, and elevated fruit yield in various crop species (Craigie, 2011; Sharma *et al.*, 2014).

Phytohormonal regulation and cell division

Brown seaweed extracts (BSEs), derived primarily from species such as *Ascophyllum nodosum* and *Ecklonia maxima*, serve as potent biostimulants in vegetable production. These extracts, rich in phytohormones (auxins, cytokinins, gibberellins, and abscisic acid [ABA]), betaines, polysaccharides, amino acids, and antioxidants, modulate plant physiological processes to enhance growth, stress resilience, and yield. In vegetable crops like tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), and pepper (*Capsicum annuum*), BSE application via foliar sprays or soil drenches has consistently improved biomass accumulation, fruit quality, and harvest index, often by 15-30% under both optimal and abiotic stress conditions. A primary mechanism driving the improved yield is the presence of endogenous plant growth regulators (PGRs) within BSEs, notably cytokinins and auxins (Khan *et al.*, 2009). Cytokinins, such as zeatin and its derivatives, are crucial for promoting cell division and differentiation, particularly in shoots, leading to increased shoot biomass and leaf area (Stirk *et al.*, 2004). Auxin-like substances, including indole-3-acetic acid (IAA) and indole-3-carboxylic acid, stimulate cell elongation and are key in enhancing root architecture, resulting in greater root length and density (Rathore *et al.*, 2009). This improved root system subsequently facilitates more efficient water

and nutrient uptake from the soil, directly supporting greater vegetative and reproductive growth. Research on crops like tomato and cucumber has shown that BSE application influences auxin and abscisic acid (ABA)-related gene expression, supporting root development and overall plant vigor (Bertoldo *et al.*, 2023; Sunarpi *et al.*, 2023). Empirical evidence confirms changes in root architecture. In a study with sugar beet (*Beta vulgaris*) treated with BSE, both total root length and fine-root length increased significantly, correlating with higher sugar yield (Carrasco *et al.*, 2022). The improved root system thus supports enhanced nutrient uptake and translocation. BSE also influences nutrient status and metabolic activity in plants. Seaweed extracts enhance enzymatic activities involved in C and N metabolism, glycolysis and the Krebs cycle (Ertani *et al.*, 2018; as cited in Puglisi *et al.*, 2023). Moreover, BSE has been shown to stimulate the expression of micronutrient transporter genes (for Cu, Fe, Zn) thereby improving mineral accumulation in plant tissues (Puglisi *et al.*, 2023). Enhanced chlorophyll content and improved photosynthetic rates, observed in crops treated with BSE, contribute to greater biomass accumulation and ultimately higher yield (Khan *et al.*, 2009). At the cellular level, BSEs promote root architecture and nutrient uptake, critical for vegetative vigor in vegetables. Cytokinins and auxins in BSEs stimulate meristematic activity, leading to increased lateral root density and mycorrhizal associations, which enhance absorption of macronutrients like nitrogen and phosphorus. In tomato seedlings, BSE treatment up regulated auxin-responsive genes (e.g., IAA family) and ABA-related pathways, resulting in 20-25% greater root length and improved sugar translocation to sinks, thereby boosting tuber or fruit yield in crops like beet (*Beta vulgaris*). This physiological priming extends to photosynthetic efficiency; betaines and osmo protectants stabilize thylakoid membranes, elevating chlorophyll a/b

ratios and net CO₂ assimilation rates by up to 18% in pepper under salinity. Enhanced stomatal conductance and Rubisco activity further amplify carbohydrate partitioning, supporting prolific flowering and fruit set in cucurbits.

Enhanced metabolism and stress resilience

BSEs also contain other essential components, including polysaccharides (e.g., fucoidans, alginates), amino acids, betaines, and various micronutrients (Battacharyya *et al.*, 2015). These components contribute to increased metabolic efficiency and abiotic stress tolerance, which indirectly boosts yield. Polysaccharides and betaines, such as glycine betaine, act as osmoprotectants and compatible solutes, helping plants maintain turgor and cell membrane integrity under stress conditions like drought or salinity (Khan *et al.*, 2009). By alleviating osmotic stress, the plant can sustain higher rates of essential physiological processes. Cytokinins delay leaf senescence, prolonging the photosynthetic life of leaves, while improved micronutrient availability, like magnesium for chlorophyll synthesis, boosts light-harvesting efficiency. Higher photosynthetic rates translate to greater carbohydrate assimilation, which is then partitioned into fruit and tuber development, resulting in a higher marketable vegetable yield (Sunarpi *et al.*, 2023). Additionally, BSEs stimulate the plant's antioxidant defense system, increasing the activity of enzymes like superoxide dismutase and catalase, which scavenge harmful reactive oxygen species (Yildiztekin *et al.*, 2018). This enhanced resilience conserves plant energy, allowing more resources to be allocated to yield production, particularly under suboptimal environmental conditions. By mitigating stress-induced physiological constraints, plants allocate more resources to productive growth rather than survival defense, leading to enhanced yield stability under suboptimal conditions. Finally, BSE may influence flowering, fruit set and yield components. Field trials show that recurring soil applications of BSE from brown algae (*Ascophyllum nodosum* / *Durvillaea potatorum*) increased wine-grape yield by an average of 14.7% across multiple seasons (Gordon *et al.*, 2021).

Implications for vegetable production and yield improvement

From an agronomic perspective, the physiological effects of BSE translate into several actionable benefits. Enhanced root growth and nutrient uptake mean that

vegetables can more effectively exploit available soil resources, potentially reducing dependence on high synthetic-fertiliser rates. The hormonal and metabolic priming induced by BSE offers an improved growth base, especially during early-vegetative phases. Moreover, improved stress tolerance makes BSE particularly appealing under climatic variability, which is critical for vegetable systems subject to fluctuations in water-availability, temperature extremes or salinity. Nevertheless, the extent of yield improvement can vary depending on extract concentration, timing of application, crop species and environmental conditions. Over-application may even be detrimental (Carrasco *et al.*, 2022), so optimization is necessary. Integration of BSE treatments into management programmes (e.g., combined with balanced fertilization, appropriate spacing) is advisable. The physiology of improved vegetable yield via brown seaweed extract involves a synergistic suite of responses: hormonal modulation of growth, enhanced root system development, improved nutrient uptake and metabolism, increased photosynthetic capacity, and elevated stress resilience. These physiological enhancements underpin consistent yield gains. With careful agronomic integration, BSE offers a promising biostimulant strategy for sustainable yield improvement in vegetable cropping systems. The improved vegetable yield following brown seaweed extract application is a result of a complex interplay of physiological mechanisms. These extracts act as potent biostimulants that promote root and shoot growth via phytohormone delivery, enhance nutrient and water use efficiency, and fortify the plant's defenses against environmental stressors by improving antioxidant capacity and photosynthetic rates. The integration of BSEs thus offers a promising and sustainable approach to maximizing crop productivity in modern agriculture.

Seaweed extracts (SWEs), commonly used as liquid biostimulants, significantly enhance plant growth, yield, and stress resilience through multiple physiological and biochemical mechanisms. Rich in natural plant hormones such as cytokinins, auxins, and gibberellins, SWEs promote photosynthesis by increasing chlorophyll content and stomatal conductance, supported by trace minerals like magnesium and iron. This leads to improved carbohydrate production, essential for growth, flowering, and fruiting. Additionally, SWE application stimulates root development by enhancing root elongation and branching, thereby improving water and nutrient uptake, particularly of nitrogen, phosphorus,

potassium, and micronutrients. These extracts also support hormonal balance, boosting flower initiation, fruit set, and reducing fruit drop. Their role in enhancing abiotic and biotic stress tolerance is attributed to the activation of antioxidant defenses and systemic acquired resistance, aided by bioactive compounds such as laminarin, mannitol, and betaines. Under stress conditions like drought or salinity, treated plants exhibit lower oxidative damage and sustain higher productivity. SWEs further improve soil health by acting as prebiotics for beneficial rhizosphere microbes, leading to enhanced nutrient cycling and root vigor. In terms of fruit quality, SWEs influence sugar accumulation, pigment synthesis, and cell wall modification, resulting in better-tasting, firmer, and more uniformly ripened fruits, as seen in elevated °Brix and lycopene levels in tomatoes. Furthermore, seed treatment with SWEs can accelerate and synchronize germination, supporting robust early plant development. Collectively, these multifaceted effects position seaweed extracts as valuable inputs for sustainable and high-efficiency crop production.

Food security

Seaweeds have been traditionally consumed for food purposes mainly in eastern Asian countries but are vastly underutilized in the western world. Statistically, the seaweed intake per capita of the Japanese population was 5.5 g DW d⁻¹, which was commonly believed as the highest. Benefiting from their micro- and macro-nutritional elements, seaweeds can be considered and further popularized as nutritional components of the human diet. Duarte *et al.*, (2022) believed that one of the feasible strategies to relieve the growing food supply stress induced by the climbing global population size is increasing the seaweed consumption of the worldwide population to half of the Japanese seaweed intake per capita. This might indeed contribute positively to the Zero Hunger goal; however, their view relied too heavily on quantitative analysis of the food demands from the growing population but ignored the seaweed production capacity and capacity growth rate.

This is because even though the goal desires only half of the per capita Japanese intake, it requires about three times of current production by 2050, which needs a 7.41% annual growth in seaweed production from now on. In comparison, seaweed production has only sustained an average of 6.2% yearly growth for the past two decades. However, to a certain extent, involving seaweeds in the human diet can relieve the boosted

stress of demand for land crops and ultimately contribute positively to worldwide food security.

Moreover, seaweeds can help with global food security issues by promoting meat production yield. Alagan *et al.*, (2020) found that the diet containing the combination of 5% *Azolla* (aquatic plant) and 3% *Ulva lactuca* (Chlorophyta) significantly increased the 60-day chicken body weight gain from 568.7 g to 816.4 g and decreased the feed conversion ratio from 4.76 to 3.39. Therefore, the feeding diet supplemented with a specific dose of seaweed not only increased the meat production yield of chicken but also boosted the feed use efficiency. This finding can be further supported by Mohammadigheisar *et al.*, (2020)'s study on broiler chicken fed. As their results suggested, the diets with adding 5–10 g/kg seaweed blend consisting of an equal proportion of two brown, one green and two red seaweeds significantly improved the chicken growth performance and breast yield. A similar effect was also observed on hens. Nhlane *et al.*, (2021) proved that adding green seaweed (*Ulva* spp.) meal within the ranges of 2–3% to hen's commercial grower diet will significantly promote the feed intake amount and overall body weight increase. In fact, this seaweed function can be enhanced after extraction. Ruiz *et al.*, (2019)'s study illustrated a proportion of 5 grams of seaweed extract per kilogram of pig feed not only boosted the slaughter weight from 90.97 kg to 92.38 kg with less fattening feed intake but also improved the gut health of nursery pigs by inhibiting the *E.coli* and promoting *Lactobacillus* sp. growth.

Intriguingly, liquid seaweed extracts (LSEs) can be used as bio-stimulants to enhance land crop growth, which can further assist with globally growing food demands. Compared to modern fertilizers, LSEs represent a sustainable tool for increasing crop production yield due to their non-toxic, biodegradable and environmental-friendly features. According to Renaut *et al.*, (2019)'s study, the addition of 250 mL 286-fold diluted *Ascophyllum nodosum* extract in pure hen manure every two weeks significantly increased the fruit number of tomatoes and fruit fresh weight of peppers. Similar effects were also observed on grain crops. Rengasamy *et al.*, (2015) believed that the eckol extracted from *Ecklonia maxima* will play an indispensable role in enhancing agricultural productivity. This is because they found the culture solution containing eckol promoted mung bean (at 10⁻⁵ M) and maize (at 10⁻⁶ M) seedling growths regarding their root length, seminal root growth,

and seedling weight. Another recent study can further support their findings. Rathinapriya *et al.*, (2020) illustrated that the foliar spray treatment of 20 + 20% (v/v) LSEs consisting of *Padina boergesenii* (Phaeophyceae) and *Gracilaria edulis* (Rhodophyta) extracts would synergistically stimulate plant growth, crop quality and yield of foxtail millet. In terms of oil crops, 400-fold diluted LSE prepared with *Sargassum* spp. powder increased leaf chlorophyll content, photosynthesis, dry matter accumulation, main stem height, and lateral branch length of peanut plants. Meanwhile, Tursun proved that applying LSE with a dose of 2 mL/L would significantly enhance the crop yield, protein content, essential oil components, and oil yield of coriander plants. Hence, there is a far-reaching significance in utilizing seaweed as an effective and sustainable fertilizer.

Health and well-beings

Seaweeds are rich in numerous essential nutrients and bioactive compounds which are beneficial for human health. Recently, Murakami *et al.*, (2021) found the diet supplemented with 6% *Sargassum horneri* ameliorated the high-fat diet-induced obesity by modulating the related metabolic disorders and suppressed the development of diabetes and hepatic steatosis by inhibiting the pancreatic lipase activity and lowering the intestinal lipid absorption in mice. Moreover, consuming seaweed has been proven to be a protective factor in preventing breast cancer. Teas *et al.*, (1982)'s study revealed the diet with 5 g day⁻¹ of *Undaria* sp. resulted in a 50% reduction in urinary human urokinase-type plasminogen activator receptor concentrations, which is a critical point that could further explain the relatively lower postmenopausal breast cancer incidence in Japan than the rest of the world. Besides breast cancer, the biocompatible gold nanoparticles (AuNPs) biogenically synthesized from *Champia parvula* (Rhodophyta) has therapeutic effects on lung cancer. Viswanathan *et al.*, (2024) indicated that the AuNPs exhibited excellent free radical scavenging ability and high cytotoxic effects against lung cancer cells. Furthermore, a recent study has revealed the relationship between seaweed intake and the remission of depressive symptoms. Guo *et al.*, (2019)'s 3-year investigation pointed out that a higher intake (>2 g/1000 kcal day⁻¹) of edible seaweeds was highly associated with a significant decrease in depressive symptom incidences. Regarding animal health, the addition of seaweeds to animal feed can modulate the gut micro flora of poultry and livestock

and enhance their immune responses. Shimazu *et al.*, (2019) reported that the addition of 1% *Undaria pinnatifida* powder had positive immunomodulatory effects on pigs by boosting the percentage of natural killer (NK) cells (CD3⁺, CD4⁺ and CD8⁺) in their peripheral blood. Instead of promoting the NK cell levels, the dietary supplementation of 2% brown and 2.5% red seaweed meals can boost the serum immunoglobulin (IgG and IgM) concentrations, thereby activating the immune responses of broiler chickens and crossbred calves,¹ respectively. Besides directly contributing to human and animal health, applying LSEs can enhance the treated crops' nutritional profile and benefit crop consumers with improved nutrition. Taking the beans (*Phaseolus vulgaris* L.) as an example, Ozaktan and Doymaz (2022) found that the LSE treatment with a 2500 mL/ha dosage had effectively improved the calcium and zinc contents and reduced the cooking time of beans.

Ecosystem services

Seaweeds have crucial ecosystem service functions. Statistically, the global seaweed communities were believed to be able to assimilate about 1.5 pentagrams annually, which is roughly equal to 10% of global car emissions. Besides, seaweeds work as an "ocean filter" and play an indispensable role in coastal water quality improvement. Taking China as an example, Zheng *et al.*, (2019)'s work estimated that aquaculture seaweeds had removed 9,592 t of phosphorus and 75,563 t of nitrogen sequestered 539,555 t of carbon and absorbed 5809 t of iodine from coastal waters, which had significantly mitigated the severe eutrophication problems faced by China. Regarding UN SDG, seaweeds have been praised for their incredible contribution to Life below water by enriching biodiversity through new biotope formation and habitat support services. Burkepile *et al.*, (2006)'s work further highlighted the role of marine algal in feeding the herbivorous fishes on coral reefs and accordingly improving the species richness on the biologic food chain and forming new biocenosis. Furthermore, the harmful effects of methane emission from ruminant animals were first emphasized by Mathison *et al.*, in 1998. What they had been worried about was further confirmed by Tenzin's recent study in 2024. They illustrated that the gas produced by ruminant enteric fermentation accounted for about 16% of the global methane emission. In fact, adding seaweeds to ruminant animal feed can substantially lessen the

formation of this greenhouse gas. Kinley *et al.*, (2020) found the *Asparagopsis taxiformis* (Rhodophyta) mixed in the high-grain total mixed ration at 0.2% resulted in a 98% decrease in enteric CH₄ emissions and a 1700% increase in H₂ production of sheep and cattle. More importantly, their study provided a sustainable option to produce carbon-neutral red meat without negatively impacting its eating quality.

In conclusion, seaweed biostimulants are an efficient and sustainable way to improve plant growth and resilience to stress. They enhance nutrient uptake, boost photosynthetic efficiency, and encourage strong root and shoot development since they are abundant in bioactive substances like phytohormones and polysaccharides. Importantly, these extracts help plants better resist biotic challenges like pests and diseases as well as abiotic conditions like drought, salinity, and severe temperatures by triggering their natural defensive systems. Their components' synergistic action frequently renders them more effective than synthetic substitutes. To guarantee consistent outcomes, research should concentrate on standardizing extraction and application techniques in future directions. More thorough research is required to pinpoint the exact biochemical and genetic pathways that are impacted by particular seaweed chemicals.

Additionally, investigating how seaweed biostimulants might be combined with other organic inputs and advantageous bacteria could lead to the development of robust and highly integrated agricultural systems. These initiatives will be essential to maximizing their potential in developing a more productive and sustainable world food supply. But it should be borne in mind that excessive application can be counterproductive.

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Satadal Das: Investigation, formal analysis, writing—original draft. Sandipan Dhabal: Validation, methodology, writing—reviewing. Sanjita Marandi:—Formal analysis, writing—review and editing. M. K. Pandit: Investigation, writing—reviewing. Swagata Mondal: Resources, investigation writing—reviewing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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