PLANT SCIENCE TODAY
Vol 12(sp1): 1-12
https://doi.org/10.14719/pst.9420

eISSN 2348-1900

REVIEW ARTICLE

A sustainable approach to enhancing fruit production and quality through seaweed based biostimulants

P Asha[1], R Jayavalli[2*], K Senthil[3], P Aruna[4], M Baskar[3], J Suresh[5], N Malini[6], S Kumar[2], P Yasodha[7], R Rajeswari[8], T Uma Maheswari[2] & Ajish Muraleedharan[9]

[1]Department of Fruit Science, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Fruit Science, Horticultural College and Research Institute for Women, Tamil Nadu Agricultural University, Trichy 620 027, Tamil Nadu, India

[3]Department of Soil Science and Agricultural Chemistry, Anbil Dharmalingam Agricultural College and Research Institute, Trichy 620 027, Tamil Nadu, India

[4]Department of Post-Harvest Technology, Horticultural College and Research Institute for Women, Navalur Kuttapattu, Trichy 620 027, Tamil Nadu, India

[5]Department of Plantation, Spices, Medicinal and Aromatic Crops, Horticultural College and Research Institute for Women, Navalur Kuttapattu, Trichy 620 027, Tamil Nadu, India

[6]Department of Basic Science, Horticultural College and Research Institute for Women, Tamil Nadu Agricultural University, Trichy 620 027, Tamil Nadu, India

[7]Department of Plant Protection, Horticultural College and Research Institute for Women, Tamil Nadu Agricultural University, Trichy 620 027, Tamil Nadu, India

[8]Department of Vegetable Science, Horticultural College and Research Institute for Women, Tamil Nadu Agricultural University, Trichy 620 027, Tamil Nadu, India

[9]Department of Floriculture and Landscape Architecture, Horticultural College and Research Institute for Women, Tamil Nadu Agricultural University, Trichy 620 027, Tamil Nadu, India

*Correspondence email - jayavallirajappa@yahoo.co.in

Received: 11 May 2025; Accepted: 26 June 2025; Available online: Version 1.0: 19 August 2025; Version 2.0: 16 September 2025

Cite this article: Asha P, Jayavalli R, Senthil K, Aruna P, Baskar M, Suresh J, Malini N, Kumar S, Yasodha P, Rajeswari R, Uma MT, Ajish M. A sustainable approach to enhancing fruit production and quality through seaweed based biostimulants. Plant Science Today. 2025; 12(sp1): 1-12. https://doi.org/10.14719/pst.9420

Abstract

Fruits play a crucial role in human nutrition by providing essential vitamins, minerals, antioxidants and dietary fiber, which support overall health and help prevent chronic diseases. Although India, being the second-largest fruit producer globally, but faces significant challenges in fruit production, including environmental stress, postharvest losses and the adverse effects of chemical-intensive agriculture. The increasing demand for sustainable farming solutions has led to the exploration of biostimulants, particularly seaweed-based formulations, which enhance plant growth, nutrient uptake and stress tolerance. Seaweed extracts are rich in bioactive compounds such as phytohormones, amino acids and antioxidants. The role of seaweed based biostimulants in modern agriculture is significant, as they positively impact on soil health, plant metabolism and on improving fruit yield, quality and resilience to abiotic stresses, environmental sustainability. Additionally, the application of seaweed extracts in fruit crops, particularly grapes, apples and citrus, has shown promising results in enhancing yield, improving fruit quality attributes and mitigating stress-related damages. The seaweed at 1 g/L was treated as a foliar treatment that can boost the anthocyanin content, increasing the yield and number of berries in grapevine *Vitis vinifera* L. The foliar application of seaweed extract at 4 mL/L increases the mineral nutrients like nitrogen, potassium, iron and zinc in the leaves of mango *Mangifera indica* L. The integration of seaweed biostimulants with precision agriculture techniques further strengthens their role in sustainable farming. Future trends in biostimulant research focus on developing cost-effective, environmentally friendly formulations with enhanced bioactivity. This study underscores the significance of seaweed-based biostimulants as a sustainable alternative to chemical fertilizers and pesticides, contributing to improved agricultural productivity while ensuring ecological balance. By adopting such innovative solutions, the agricultural sector can enhance fruit production efficiency, minimize losses and promote long-term sustainability in horticulture.

Keywords: abiotic stress mitigation; bioactive metabolites; crop productivity; hormonal regulation; seaweed extracts

Introduction

Fruits are essential for human nutrition and health serving as rich sources of vitamins, minerals, dietary fiber, antioxidants and phytonutrients (1). According to the Ministry of Agricultural and Farmers Welfare, India is the world's second largest fruit producer, behind China, with production increased to 112.63 Mt in 2021-22. Additionally, fruits support digestive health, enhance metabolic processes and contribute to overall well-being by supplying essential nutrients like calcium, potassium, sodium and proteins. Their antioxidant properties further protect the body and promote optimal health (2). They provide 91 % of the recommended vitamin C, 48 % of vitamin A, 27 % of vitamin B, 17 % of thiamine, 15 % of niacin, 16 % of magnesium and 19 % of iron. These nutrients are vital for the body's proper functioning and play a key role in preventing diseases such as cancer, heart disease, stroke and other chronic conditions (3). For example fruits like grape, blueberry, pomegranate, apple, hawthorn and avocado have been extensively researched and demonstrated significant cardiovascular benefits (4). Fruit losses are greatly impacted by environmental conditions, which have an effect on both quantity and quality. Environmental factors such as climate, postharvest handling and plant physiological responses significantly influence the yield and quality of fruit crops. Cultivar-specific reactions to environmental stresses are common, with fluctuations in temperature playing a key role in fruit drop and abscission (5). The increase in fruit production over recent decades has largely depended on the intensive use of chemical fertilizers and pesticides. While this approach improved yields during the Green Revolution, it also led to widespread concerns over soil health, environmental degradation and food safety (6). Such impacts have challenged the long-term sustainability of agricultural and horticultural practices, underlining the importance of adopting integrated and environmentally sound management strategies. In tropical fruit crops, factors like respiration rate, ethylene sensitivity and environmental stress, particularly heat and humidity, are major contributors to postharvest losses (7). Abiotic stresses, including extreme temperatures, bring about physiological and biochemical changes that negatively affect fruit development and quality, making the use of proper irrigation strategies and the selection of stress-tolerant cultivars essential (8,9). These stresses not only reduce productivity but also contribute to significant postharvest losses (10). Furthermore, increasing global food and energy demands, driven by population growth and climate instability, reinforce the urgent need for sustainable agricultural solutions (11).

In recent years, the need for environmentally sustainable and resource-efficient agricultural inputs has become increasingly urgent due to the adverse impacts of climate variability, soil degradation and the overuse of synthetic agrochemicals. Within this context, biostimulants, particularly those derived from natural sources, have emerged as promising tools for enhancing crop performance without harming environmental or human health. Among the various categories of biostimulants, seaweed-based formulations are notable for their diverse composition of bioactive molecules such as phytohormones, vitamins, amino acids, polysaccharides and antioxidants. These compounds can influence key physiological processes, thereby improving nutrient uptake, enhancing tolerance to abiotic stress and contributing to better fruit development and postharvest quality.

Although there is growing interest in the use of seaweed -derived biostimulants in crop production, the literature specifically focusing on fruit crops remains scattered. Considering the high commercial value of fruits and their sensitivity to environmental stressors, it is essential to consolidate current research to better understand the mode of action, benefits and practical applications of these biostimulants in fruit production systems. This review aims to critically assess recent scientific findings, identify potential benefits and limitations and provide insights into how seaweed-based biostimulants can be integrated into sustainable fruit crop management practices.

Biostimulants

Biostimulants are primarily bio-based products that improve resistance to unfavorable circumstances such high soil pH, salinity, drought, heat and nutritional stress by enhancing primary and secondary plant metabolism and others have demonstrated that biostimulants, which are rich in macro- and micronutrients, sterols, polysaccharides, betaines and growth-promoting compounds, improve agronomic performance, water and nutrient absorption, photosynthesis and pigment concentration, including carotenoids and phenols (12,13). They also affect molecular functions such as photosynthetic efficiency, enzyme activity and protein synthesis (14). The classification of biostimulants are depicted in Table 1. Among these bio-stimulants seaweed plays an significant role in fruit crops.

Table 1. Classification of biostimulants (15)

Category	Subcategory	Examples/ Componnents
Nonmicrobial	Acids	Amino acids Fatty acids and lipids Humic and fulvic acids Other organic acids
	Extracts	Plant derived bioactives Seaweed Chitosan
	Others	Protein hydrolysates Enzymatic extracts Inorganic salts Vitamins
Microbial	Beneficial microbes	Beneficial fungi Beneficial bacteria
	Others	Microbial symbiosis Other microbial biostimulants
Waste- Derived	Sources	Food waste Industrial by-products Agricultural by-products

Different type of seaweed

Seaweeds, also known as macroalgae, are marine, photosynthetic, non-flowering and plant-like organisms. Three groups of seaweeds are distinguished by their photosynthetic pigment: red (*Rhodophyta*), green (*Chlorophyta*) and brown (*Ochrophyta* or class *Phaeophyta*). Approximately 10000 seaweed species exist, comprising roughly 6500 red, 1500 green and 2000 brown seaweeds (16). The classification of seaweed is shown in Table 2 (17,18). From warm to cold arctic locations, seaweeds can be found along the world's coastlines (19). About 83 % of seaweed produced worldwide is used directly for human consumption in Asian nations; it is frequently eaten fresh, dried or as a component of other meals (20). The remainder is used in a variety of industries, including medicine, cosmetics, food applications and other related fields (21-24). There are 221 species of seaweeds that are utilized in total, 101 seaweed species are used to produce phycocolloids, while 145 are used as food (25). Additionally, seaweeds are used as

Table 2. Classification of seaweed (17,18)

Division (Phylum)	Common name	Pigment present	Example species
Chlorophyta	Green algae	Chlorophyll a & b, beta-carotene	*Caulerpa peltata, Caulerpa racemosa, Caulerpa racemosa* var. *macrophysa, Caulerpa scalpelliformis, Caulerpa sertularioides, Caulerpa taxifolia, Chaetomorpha aerea, Chaetomorpha antennina, Chaetomorpha crassa, Chaetomorpha linum, Chaetomorpha linoides, Codium adhaerens, Codium decorticatum, Codium tomentosum, Enteromorpha compressa, Enteromorpha prolifera, Halimeda gracilis, Halimeda macroloba, Halimeda opuntia, Ulva fasciata,* etc.
Phaeophyta	Brown algae	Chlorophyll a & c, fucoxanthin	*Chnoospora implexa, Colpomenia sinuosa, Dictyopteris delicatula, Dictyota bartayresiana, Dictyota dichotoma, Hydroclathrus clathratus, Lobophora variegata, Padina boergesenii, Padina gymnospora, Padina pavonica, Padina tetrastromatica, Rosenvingea intricata, Sargassum cinereum, Sargassum natans, Sargassum cristaefolium, Spatoglossum soleri, Sargassum plagiophyllum, Sargassum ilicifolium, Sargassum polycystum, Sargassum tenerrimum, Sargassum wightii, Apatoglossum asperum, Stoechospermum marginatum, Turbinaria conoides, Turbinaria decurrens, Turbinaria ornata, Dictyota indica,* etc.
Rhodophyta	Red algae	Chlorophyll a & d, Phycoerythrin	*Porphyra indica, Acanthophora spicifera, Amphiroa anceps, Amphiroa fragilissima, Centroceras clavulatum, Champia parvula, Gelidiella acerosa, Gracilaria arcuata, Gracilaria canaliculata, Gracilaria corticata, Gracilaria edulis, Gracilaria folifera, Gracilaria megaspora, Gracilaria spinulosa, Gracilaria textori, Grateloupia filicina, Grateloupia lithophila, Halimenia dilatata, Halimenia floresia, Halimenia venusta, Hypnea musciformis, Hypnea pannosa, Hypnea valentiae, Portieria hornemanii,* etc.

fertilizers, water purifiers, animal feed additives and aquaculture probiotics (26-29). Seaweeds are well known for their capacity to generate a wide variety of macromolecules with biological activity. Pigments, phenolic compounds, lipids, proteins, vitamins, minerals and carbohydrates (polysaccharides) are important elements of seaweeds (30). According to numerous studies, algae are the most plentiful source of these bioactive substances, especially polysaccharides that can be either sulfated or non-sulfated (31). Alginates and laminaran are examples of non-sulfated polysaccharides, whereas agars, carrageenans, fucoidans and galactans are examples of sulfated polysaccharides (24).

Seaweed extract

Seaweed extracts, which are biostimulants derived from seaweed, particularly red and brown algae, can improve soil health, increase crop stress resistance and stimulate crop growth (32). The major seaweed extract producing states are Tamil Nadu, Gujarat, Maharashtra, Goa, Lakshadweep, Andhra Pradesh and Karnataka (33). They function as chelates that improve soil mineral elements, plant nutrient uptake, soil structure and soil aeration qualities, all of which eventually encourage root growth (34). Additionally, seaweed extract has been employed as a liquid biostimulant to improve plant resistance to drought and salinity. Through nutrient absorption and assimilation, this biostimulant also influences the bioactive content of plants (35). The bioactive compounds present in seaweed extract are shown in Fig. 1.

Different methods of seaweed extraction

The foremost step is the extraction of seaweed. The seaweed extraction techniques are shown in Table 3 (36). The seaweed species examined, depend upon their solvent, temperature, time, pH, environmental impact, cost, quantity and desired qualities all affect the method selection and extraction efficiency (37). Seaweed extract contains various polysaccharides, proteins, unsaturated fatty acids, pigments and minerals such as potassium (K), magnesium (Mg), calcium (Ca) and sodium (Na) and these compounds varies depending upon their species (38). The proximate composition of three seaweed groups green, brown and red was analyzed and presented as mean ± SE based on three replicates using one-way ANOVA and Tukey's comparison test. The moisture

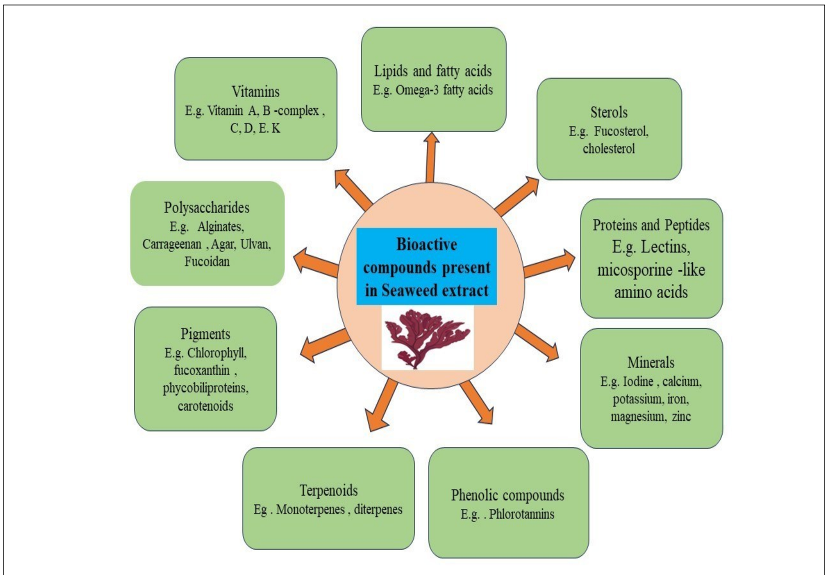


Fig. 1. Bioactive compounds present in seaweed extract.

Table 3. Seaweed extraction techniques

Method	Types	Overview	Pros	Cons	References
Traditional Extraction	Solid-Liquid Extraction (SLE)	Relies on dissolving the desired compound in a suitable solvent, may involve acids or bases to enhance extraction.	Well established and commonly used approach.	Time consuming requires large quantities of solvents and chemicals, which can harm polysaccharides.	
Green Extraction	Microwave Assisted Extraction (MAE)	Employs microwave energy to adjust variables like temperature, pressure and duration to improve extraction output.	Quick process with minimal solvent usage	Elevated temperatures may break down polyphenols.	
	Ultrasound assisted Extraction (UAE)	Utilizes ultrasonic waves to facilitate extraction under mild conditions with limited solvent.	Fast method, operates at low temperatures, uses little solvents and avoids compound breakdown.	May alter or degrade the structure of polysaccharides	
	Supercritical Fluid Extraction (SFE)	Makes use of supercritical CO_2 for compound extraction.	Does not damage the chemical structure of extract.	Needs high pressure to retain CO_2, which can adversely affect the final product.	
	Pressurized Solvent Extraction (PSE)	Involves high pressure techniques like PLE, PFE, ASE, or HPSE to enhance solubility and diffusion.	Provides efficient extraction similar to Soxhlet but with better solvent performance.	Balancing temperature and pressure to optimize extraction can be challenging.	(36)
	Enzyme Assisted Extraction (EAE)	Applies enzymes such as cellulase and hemicellulase to break down cell walls and release target compounds.	Avoids chemical solvent and offers high extraction yields.	Results vary based on enzyme type, pH, temperature and duration.	

content was found to be 95.71 ± 1.02 % in green seaweed, 95.12 ± 0.56 % in brown seaweed and 94.82 ± 0.45 % in red seaweed. The dry matter content was 4.16 ± 0.95 % for green, 5.13 ± 0.55 % for brown and 5.06 ± 0.51 % for red seaweed. Ash content was highest in green seaweed at 23.06 ± 5.98 %, followed by brown at 13.59 ± 3.78 % and red at 12.88 ± 3.04 %. Lipid content varied significantly across groups, with green seaweed containing 0.22 ± 0.73 %, brown seaweed 3.543 ± 0.43 % and red seaweed 2.15 ± 0.29 %. Protein levels were 15.64 ± 2.11 % in green seaweed, 24.13 ± 6.30 % in brown and 26.69 ± 2.21 % in red seaweed. Total dietary fiber was found to be 56.13 ± 6.05 % in green seaweed, 54.48 ± 6.58 % in brown seaweed and 53.57 ± 3.18 % in red seaweed (39). It also contains flavonoids and polyphenolic compounds, including phlorotannins, bromophenols, flavonoids and phenolic terpenoids (40). The phenolic compounds are difficult to isolate due to their reactivity with other substances, they can be successfully extracted on a laboratory scale (41).

Traditional method for extracting seaweed involve hot water extraction, which is eco-friendly and eliminates the need for organic solvents (42). Acidic or alkaline solutions, such as KOH and NaOH, can also be used for seaweed extraction (43). Techniques like Soxhlet extraction, TLC-based method and High-Speed Counter-Current Chromatography (HSCCC) have been refined to extract pigments and isolate seaweed compounds effectively (41). However, Solid-Liquid Extraction (SLE) are not suitable for large quantities of organic solvents, extended extraction times, limited selectivity and the co-extraction of undesirable compounds (44). Similarly, Liquid-Liquid Extraction (LLE) uses a lot of organic solvents, which can create harmful waste. To overcome these issues, green extraction methods using minimal organic solvents and biodegradable materials have been proposed as sustainable alternatives (45).

Green extraction techniques such as Microwave-Assisted Extraction (MAE) (42), Ultrasound-Assisted Extraction (UAE) (46), Supercritical Fluid Extraction (SFE) (40), Pressurized Solvent Extraction (PSE) (44) and reactive extrusion have proven effective in enhancing the yield of seaweed extract. These methods offer benefits such as reduced reliance on organic solvents, higher selectivity, lower operating temperatures and shorter extraction times (47). Combining these techniques has also been shown to produce superior seaweed extracts. Methods that are environmentally friendly, cost-effective, rapid, sensitive and accurate are increasingly preferred over traditional extraction approaches (37,48). The Schematic representation of the seaweed extraction method is shown in Fig. 2.

Methods of applying seaweeds and their extracts in horticulture

Seaweed biomass and seaweed meal

Various methods have been employed to apply seaweed products to horticultural crops, with the choice depending on the form of the product, such as meal, powder or extract. The use of whole seaweed biomass or meal is particularly common in coastal regions where seaweed is readily available. Typically, whole seaweeds or seaweed meal are spread over the soil and incorporated to encourage microbial decomposition. This process is conducted well before planting, as the decomposition phase can temporarily deplete soil nitrogen, leading to a short-term nutrient deficiency that may hinder plant growth. Once decomposed, the seaweed contributes organic matter that enhances soil physical and chemical properties, improves water retention, boosts microbial activity and offers protection against adverse environmental conditions such as extreme temperatures, water stress or nutrient imbalances (49).

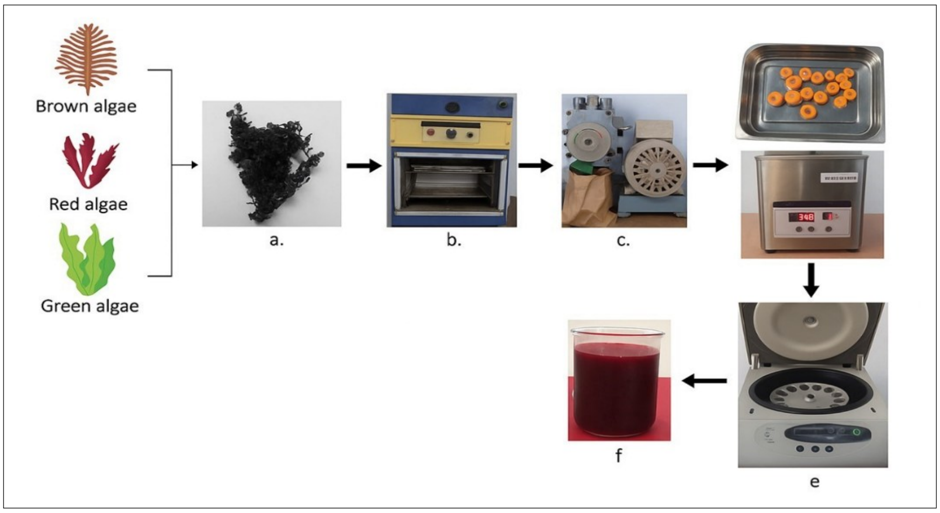


Fig. 2. Schematic representation of the seaweed extraction method.

a. Dry seaweed; b. Drying (hot air oven); c. Grinding (Willey Mill); d. Extraction (ultrasonicator); e. Separation (centrifugation); f. Crude extract.

Seaweed extract

Seaweed extracts are among the most commonly utilized seaweed products in horticulture, available in liquid or soluble powder form. Liquid extracts can be applied near plant roots by mixing them with irrigation water and administering through drip irrigation systems. In sour orange (*Citrus aurantium* L.), fertigation with seaweed extracts at 4 g/L can boost the bloom count per plant and the fruit quality (50). Additionally, seaweed extracts are frequently used as foliar sprays on various crops, including flowers, vegetables and trees such as potatoes, tomatoes, plums, cherries, almonds and mangoes (51). Foliar application is most effective when performed in the morning when leaf stomata are open. The effectiveness of seaweed extracts also varies with the plant's growth stage.

Nano seaweed

The possibility of seaweeds' exploitation in modern agriculture has been widely explored and different varieties of preparations of these marine algae as liquid fertilizer and either whole or finally chopped powdered algal manures are being used. The interest in nano-fertilizers and preparations that stimulate plant growth and development is increasing constantly and it may become one of the futures. Broadening the knowledge on bioregulators can result in an increase in the effectiveness of agricultural production as well as in the quality of crops. Nano seaweed extract from its counterparts by having a high surface area and a high speed to penetrate the plant tissues, which may be sprayed on the plant to elicit a high response, faster assimilation, growth and higher yield (52).

The increase of growth parameters of barley may be attributed to plants treated with nano seaweed extract, which exhibited robust vegetative growth, maybe due to their concentration of essential nutrients for development, such as nitrogen, significantly enhancing crucial plant functions, hence promoting growth. It is assimilated by the plant's growth, which signifies enhanced development and results in an increased number of spikes (53).

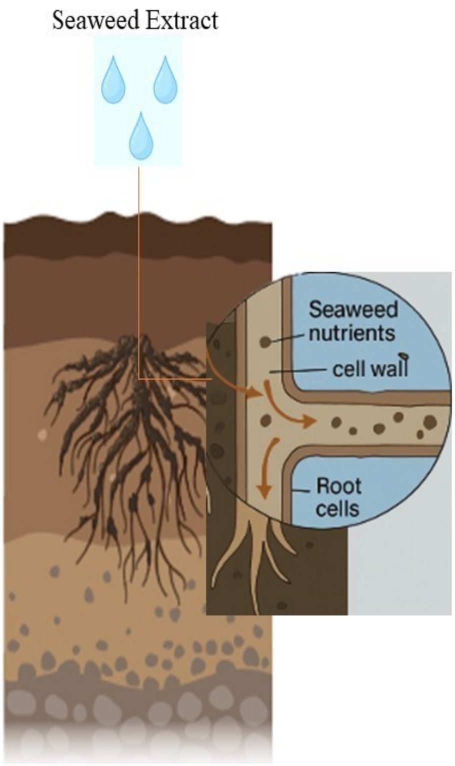
Plant nutrient uptake

Plants absorb nutrients through roots or leaf surfaces and seaweed extracts significantly enhance this process by modifying soil properties and root architecture, thereby facilitating efficient nutrient uptake (49). Brown seaweeds, containing polyuronides like alginates and fucoidans, improve soil water retention and microbial activity through the formation of cross-linked polymers (54). Extracts from *Ecklonia maxima* have been demonstrated to promote root growth in tomatoes and mung beans (55).

Seaweed-based products also influence rhizosphere chemistry. They enhance the activity of beneficial soil microorganisms, leading to improved nutrient solubilization and cycling. The organic compounds present in seaweed extracts stimulate root exudation, which further supports microbial proliferation and enzymatic functions in the soil. This results in better nutrient availability, particularly of phosphorus and trace elements, contributing to enhanced root development and soil fertility. For example, a vitamin K1 derivative in commercial extracts acidifies the rhizosphere, enhancing the solubility of metal ions like iron and copper, which plants readily absorb (56). Additionally, seaweed extracts regulate key genes for nutrient uptake, such as the nitrate transporter gene *NRT1.1*, which improves nitrogen sensing and lateral root growth (57). Extracts from *Ascophyllum nodosum* have been shown to increase nitrogen-fixing nodules in leguminous plants by activating bacterial genes critical for plant-microbe signaling (58).

Foliar application of seaweed extracts has been particularly effective in enhancing the uptake of nutrients like copper in grapevines, iron in lettuce and calcium in *Brassica oleracea*, especially under stressful or nutrient-deficient conditions (59). The nutrients in seaweed extracts are readily absorbed through leaf stomata and their uptake efficiency is influenced by environmental factors such as temperature, humidity and light intensity (60).

Additionally, applications of *E. maxima* extracts improved the yield and mineral content (Ca, K, Mg) of lettuce leaves (60). Seaweed-based products have been shown to enhance nutrient content (N, P, K, Ca, Zn and Fe) in tomatoes, as observed in studies on commercial brown seaweed extracts (61). These findings underscore the multifaceted benefits of seaweed extracts in promoting nutrient uptake and plant



Application Method	Mechanism of Nutrient Entry	Target site	Suitable Crops/Stages
Foliar spray	Penetrates leaf cuticle and stomata	Leaf surface a initial tissues	Vegetative and reproductive stages
Seed Treatment	Enters during imbibition	Seed embryo a radicle	Pre –sowing treatment
Soil Application	Absorbed by roots from soil	Roots, rhizosphere	Perennial and annual crops, early stages
Fertigation	Absorbed through root membranes	Root Zone	Row crops, fruit trees, vineyards
Root dipping	Absorbed by epidermal cells	Sustained nutrient availability	Nursery seedlings, vegetables

Fig. 3. The mechanism of seaweed nutrients entry to plant with application methods.

Table 4. Effect of seaweed extract on fruit crops

Seaweed Extract	Crop	Effect	Reference
Ascophyllum nodosum extract	Grapevine cultivars like Sangiovese, Pinot Noir and Cabernet France	It improves the accumulation of anthocyanin in all cultivars and particularly phenolic content is increased in Sangiovese.	(67)
Seaweed extract of (*Sargassum*) with amino acid	Grapevine cultivars Arra 15 and Arra 20	Arra 15 CV was superior in cluster weight (g) and cluster length (cm) compared to Arra 20 CV. Arra 20 CV was superior in cluster width (cm) and cluster round (cm) compared to Arra 15 CV. It has also increased yield per vine and fruit quality compared to control.	(68)
Boron ethanolamine plus zinc oxide and brown algae *Ascophyllum nodosum*	Grapevine variety Carmenere	It improves the fruit set, bunch weight and number of berries per bunch.	(69)
Commercial seaweed extracts Kelpak extracted from *(Ecklonia maxima*) and Geomar BM 86 extracted from *Ascophyllum nodosum*	Apple trees Gala Must, Golden Delicious, Jonagold Decosta and Elstar	It stimulated the growth of shoots and leaves and improved flower quality and prolonged blooming time. They showed a small effect on the size distribution of apples.	(70)
Arbuscular mycorrhizal fungi+ seaweed extract of *Ascophyllum nodosum*+ Nano zinc oxide particles	Early Sweet grapevines	It improved vegetative growth, leaf content of mineral elements, weight of pruning wood, cane content of total carbohydrates and yield. It enhances the quality of clusters and berries, especially the percent of shot berries and compactness coefficient of the cluster.	(71)
Extracts of Macroalgae Green*(Ulva flexusoa,E nteromorpha intestinalis* and red *Griffithsia teges)*	Valencia orange	Significant levels of various phytohormones, such as IAA, GA_3, ABA and CK has increased. Green algae contain the highest concentration of GA_3 and cytokinin was observed only in *G. teges.* Macroalgae extract significantly affected the mineral composition of orange leaves and chlorophyll content and the green algae impacted fruit quality characters, including weight, length and width, juice volume, TSS and peel color. Significant improvement in growth, leaf pigments and nutrient levels. The quality attributes of fruit were enhanced with increased yield.	(72)

Seaweed extract of *(Ascophyllum nodosum)* and glycine betaine	Grapes cultivar Touriga France	Both ANE and GB increase the anthocyanin and phenolic content synthesis in berries. They also influenced the expression of genes related to the synthesis and transport of anthocyanins (CHS, F3H, UFGT, MATE1 and GST). They have the potential to act as elicitors of secondary metabolism; it leads to improved grape quality.	(73)
Commercial extract (Gifert) modified of *Ascophyllum nodosum,* effective microorganism and aminoacids	Grapes (Red Globe)	The combined application of EM, Gifertand Pepton gave the best results compared to control best yield, the best physical characteristics of bunches, improved physical and chemical characteristics of berries and the best vegetative growth parameters. The total chlorophyll and percentages of total amino acids, nitrogen, phosphorus and potassium in leaves and total carbohydrates in the canes were increased. Also, the microbiological activity in the rhizosphere noticed that the total spore-forming population of total microorganisms and dehydrogenase and phosphatase enzyme activity increased in the rhizosphere combined application of EM, Gifert and amino aminoacids (Pepton) at the higher rate when compared to the control.	(74)
Ascophyllum nodosum extract	Grapevine cultivar Feteasca Alba	Vegetative growth has been stimulated with high shoot length, shoot diameter and leaf area.	(75)
Seaweed extract of *Ascophyllum nodosum* and humic acid	Cultivar Riesling wine grape	It effectively improves the biochemical and aromatic qualities of Riesling grapes.	(76)
Seaweed extract + Chitosan extract and Fulvic acid	Grape (*Vitis vinifera* cv. Ruby Seedless	Among natural plant extracts, chitosan, seaweed extract and fulvic acid were most effective in enhancing the yield and cluster weight of Ruby Seedless grapes. Salicylic acid showed the best results among synthetic treatments. Salicylic acid was the most effective synthetic chemical, while the combination of free amino acids + fulvic acid produced the highest improvements in yield and cluster weight.	(77)
Seaweed extract and Chitosan	Flame seedless grapevines	The effects of foliar sprays of chitosan (100-400 ppm) and seaweed extract (0.05–0.2 %), applied either alone or in combination. The treatments were carried out three times during each growing season. The findings showed that these applications improved vine growth, leaf pigment levels, nutrient uptake, fruit yield and both the physical and chemical characteristics of the berries compared to untreated vines. Higher concentrations generally led to better results, although the improvement between the top two concentrations was minimal.	(78)
Seaweed extract of *Ascophyllum nodosum* and effective microorganisms	Grapevine cultivar Ruby Seedless	All treatments positively influenced vegetative growth, shoot length, leaf area, berry chemical traits and overall yield. The most effective combination was 1 g/L EM with 2 g/L seaweed extract, which resulted in the highest yield and the lowest percentage of shot berries compared to the untreated control.	(79)
Seaweed extract, humic acid and brassinosteroids	Apricot (*Prunus armeniaca* cv. Canino)	Results revealed that all biostimulant treatments significantly enhanced shoot growth, leaf area, chlorophyll content, fruit set, total yield and the physical and chemical characteristics of the fruits. Furthermore, the treatments improved leaf nutrient content, both macro- and micronutrients. The improvements were more pronounced with increasing concentrations of each biostimulant, where the highest doses of HA, Brs and SWE consistently outperformed the lower and moderate levels.	(80)
Ascophyllum nodosum + Microbial biostimulant	Strawberry cultivars (Sweet Sensation VR Florida127 and Florida Brilliance).	The combined treatment consistently improved plant growth, nutrient uptake and yield, increasing marketable and total fruit yields by 23 % and 20 %, respectively, over the untreated control. It also enhanced root architecture, nitrogen absorption, crown number and soil respiration. While fruit quality traits like soluble solids, acidity and anthocyanin content were not significantly affected by treatments, cultivar differences were evident. 'Florida Brilliance' outperformed 'Florida127' in yield, marketable fruit number, photosynthetic rate, SPAD index and mineral content, highlighting both the effectiveness of the biostimulant combination and the genotypic influence on strawberry performance in organic systems.	(81)
Seaweed extract of *Ascophyllum nodosum*	Strawberry	Among the concentrations tested, 0.2 % ANE was the most effective, reducing spore germination by 75 % in greenhouse trials. Plants treated with ANE also exhibited enhanced resistance to powdery mildew, as indicated by increased levels of total phenolics and flavonoids, along with elevated activity of defense-related enzymes like phenylalanine ammonia lyase, polyphenol oxidase and peroxidase. Under field conditions, foliar application of 0.2 % ANE reduced the natural incidence of powdery mildew by 37.2 % compared to untreated plants and also decreased disease severity.	(82)

Macroseaweed	Apple (*Malus domestica*), cultivar Jonathan.	Macro-seaweed extract significantly promoted vegetative growth, leading to about a 20 % increase in leaf surface area, enhanced chlorophyll content and improved photosynthetic activity. Applications of macro-seaweed, B-vitamins and alfalfa hydrolysate also contributed to better fruit coloration and higher levels of anthocyanins in the fruit peel, particularly in the more favorable growing conditions of 2016. Moreover, combining amino acids with zinc was highly effective in lowering the incidence of the 'Jonathan spot' postharvest disorder by over 50 %.	(83)
Silicon and seaweed extract	Papaya cultivar Red Lady.	Among the treatments, the combined foliar application of 0.2 % ortho silicic acid and 2 % seaweed extract significantly enhanced fruit quality traits, recording the highest values for Total Soluble Solids (TSS), total sugars, reducing sugars, ascorbic acid and β-carotene. Additionally, the thickest pulp was observed with the application of seaweed extract at 4 %.	(84)
Seaweed extract of *Ascophyllum nodosum* and growth regulators (GA_3 and NAA	Winter guava trees cv. Maamoura	The best results were obtained with GA_3 at 3 mg/L and seaweed extract at 15 mg/L, which significantly improved vegetative growth, chlorophyll content, fruit set, yield and TSS. These treatments also increased leaf nutrient content (N, P, K), fruit number,	(85)
Wood Vinegar (WV), Seaweed Extract (SW) and Humic Acid (HA)	Mango cultivar Ewais	It has increased total chlorophyll content to 107.7 % and 106.6 %, leaf nitrogen to 2.02 % and 2.23 %, phosphorus to 0.38 % and 0.40 % and potassium to 1.07 % and 1.13 % in the 2023 and 2024 seasons, respectively. Additionally, fruit quality improved, with fruit length reaching 11.68 cm and 12.38 cm, fruit width increasing to 7.8 cm and 8.59 cm, total sugars rising to 40 % and 37.3 % and TSS values reaching 21.9 % and 20.8 %. Total acidity was also reduced by 64.3 % and 69.0 % in the two seasons.	(86)
Seaweed extract of *Durvillaea potatorum* and *Ascophyllum nodosum*	Wine grapes 5 cultivars Chardonnay, Semillon, Merlot, Merlot, Cabernet Sauvignon	Results indicated a consistent yield increase averaging 14.7 %, even under varying and extreme climate conditions. Economic analysis further demonstrated profitability improvements, which varied by cultivar.	(87)
Seaweed extract of *Ascophyllum nodosum*	Sweet orange (Hamlin) on Carrizo citrange and Swingle citrumelo rootstocks	Seaweed extract-treated trees under drought conditions showed significantly more total growth compared to untreated drought-stressed trees, regardless of rootstock. Although photosynthetic rates were not directly affected by the seaweed extract, a notable improvement in plant water relations was observed. Soil drench-treated trees had greater total growth and higher stem water potential than those receiving foliar sprays or no treatment.	(66)
Ascophyllum nodosum extract	Banana (Grand Naine)	Enhances growth, early flowering, improved fruit quality and bunch weight. - Combined application of 0.05 % potassium silicate and 0.05 % seaweed extract resulted well	(88)
Gebberellic acid and seaweed extract	Peach cultivar Peento	The combined treatment of GA at 100 mg/L and seaweed extract at 4 mL/L ($GA_{100}SF_4$) produced the highest values Across two seasons for total leaf area (2316 and 3115 cm^2), chlorophyll content (36.33 and 37.18 mg/g), leaf carbohydrates (12.14 % and 12.65 %), nitrogen content (1.82 % and 1.94 %) and zinc content (22.39 and 25.21 ppm). The lowest values were observed in the untreated control (GA_0SF_0).	(89)
Actiwave a metabolic enhancer is derived from *Ascophyllum nodosum*	Apple (Fuji)	Actiwave generally helped mitigate the effects of alternate bearing, especially in nutrient-deprived trees. It reduced yield fluctuations between heavy ("on") and light ("off") years and improved average fruit weight in trees with excessive fruit loads. Additionally, treated trees exhibited a 12 % increase in leaf chlorophyll content, which was associated with enhanced photosynthesis and respiration rates.	(90)

Actiwave derived from *Ascophyllum nodosum*	Strawberry	The treatment led to significant improvements, including a 10 % increase in vegetative growth, 11 % higher chlorophyll content, 6.5 % increase in stomatal density, enhanced photosynthetic rate and a 27 % increase in both fruit production and shoot dry weight. Root dry matter rose by 76 %. Additionally, Actiwave positively affected the root microbial community.	(91)
The preparation of TAM True-Algae-Max by using seaweed species *Ulva lactuca* (Chlorophyceae), *Jania rubens* and *Pterocladia capillacea* (Rhodophyceae)	Strawberry	The most notable improvements in plant growth parameters such as root length, leaf area, fresh biomass, fruit weight and overall yield, showing enhancements ranging from 10 % to 110 % over untreated controls. Additionally, fruit quality improved significantly, with increase in TSS (from 7.58 % to 10.12 %) and anthocyanin content (from 23.08 to 29.42 mg CGE per 100 g). TAM application also led to a reduction in total sugar and non-reducing sugar, while boosting total phenolic content**.**	(92)

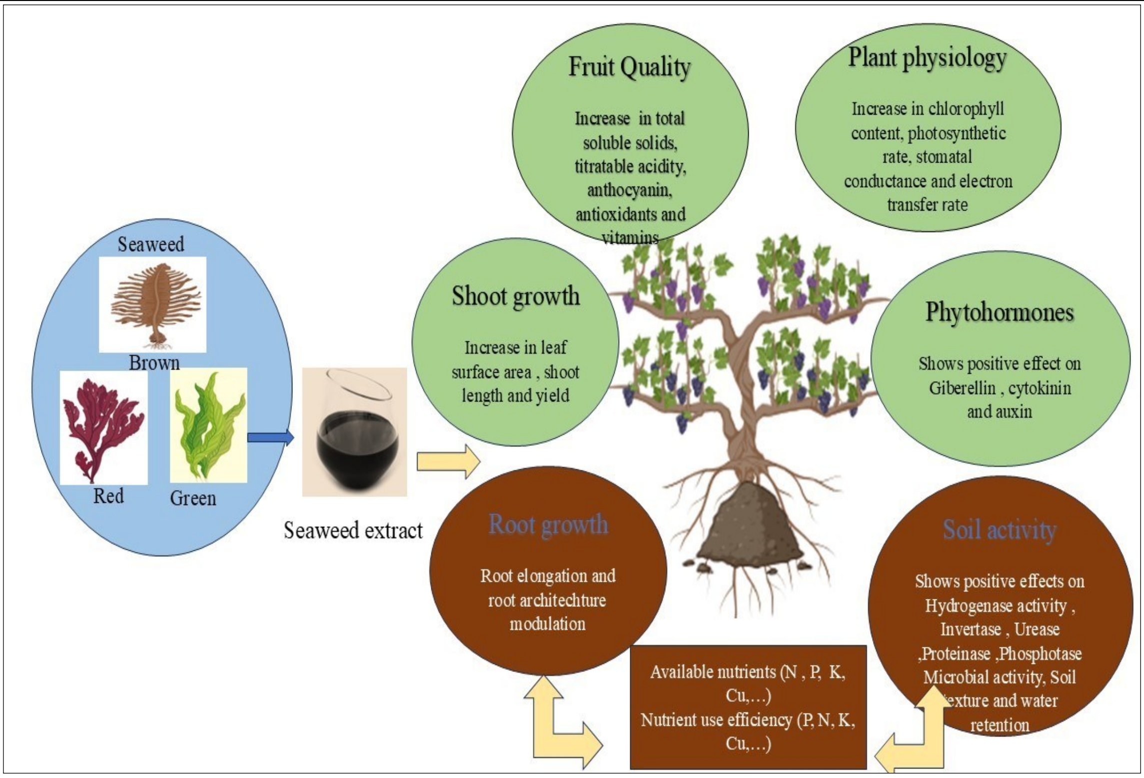


Fig. 4. Beneficial effects of seaweed extract on plant growth and development.

health. The Mechanism of seaweed nutrients entry to plant with application methods is shown in Fig. 3.

Effect of seaweed extract on fruit crops

Multiple studies have demonstrated that the application of seaweed extract to plants offers a variety of benefits, such as enhancing early seed germination and establishment, improving crop productivity and yield, increasing resilience to biotic and abiotic stressors and prolonging the post-harvest shelf life of perishable products (62). Soil drenching with seaweed extract in *Citrus* (*Citrus* spp.) promotes plant growth (63,64). Foliar application of seaweed extract in Almond *Prunus dulcis* increase the shoot biomass and shoot length (65). Soil drenching of seaweed extract in *Citrus* spp. mitigates the drought stress and increases the stem water potential, as well as the growth of the plant (66). Effect of seaweed extract on fruit crops is represented in Table 4. Beneficial effects of seaweed extract on plant growth and development is depicted in Fig. 4.

Conclusion

Seaweed-based biostimulants offer a promising approach to enhancing fruit crop performance by improving growth, yield and tolerance to environmental stresses. Their natural origin and rich composition of bioactive compounds make them suitable for sustainable agriculture. However, their widespread adoption is constrained by certain limitations. Variability in extract composition due to differences in seaweed species, processing techniques and environmental conditions can lead to inconsistent results. Moreover, the lack of standardized application protocols, limited large-scale field studies and relatively high production costs may hinder practical implementation. Future research should focus on formulation consistency, mode of action and cost-effective production to fully harness their potential in modern fruit cultivation systems.

Acknowledgement

We are grateful to Tamil Nadu Agricultural University for their ongoing support in the form of regular workshop that helps us with writing review.

Authors' contributions

PA[1] prepared the original draft. RJ contributed to the conceptualization. KS participated in sequence alignment, editing and visualization. PA[2] and MB supervised the work and were involved in drafting and reviewing the manuscript. JS, NM, SK, PY, RR, TUM and AM contributed to language editing and validation. All authors have read and approved the final version of the manuscript. [PA[1] stands for P Asha and PA[2] stands for P Aruna]

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Van Duyn MAS, Pivonka E. Overview of the health benefits of fruit and vegetable consumption for the dietetics professional: selected literature. J Am Diet Assoc. 2000;100(12):1511-21. https://doi.org/10.1016/S0002-8223(00)00420-X
2. Riordan F, Ryan K, Perry IJ, Schulze MB, Andersen LF, Geelen A, et al. A systematic review of methods to assess intake of fruits and vegetables among healthy European adults and children: a DEDIPAC (DEterminants of DIet and Physical Activity) study. Public Health Nutr. 2017;20(3):417-48. https://doi.org/10.1017/S1368980016002366
3. Collese TS, Nascimento-Ferreira MV, de Moraes ACF, Rendo-Urteaga T, Bel-Serrat S, Moreno LA, et al. Role of fruits and vegetables in adolescent cardiovascular health: a systematic review. Nutr Rev. 2017;75(5):339-49. https://doi.org/10.1093/nutrit/nux002
4. Zhao CN, Meng X, Li Y, Li S, Liu Q, Tang GY, et al. Fruits for prevention and treatment of cardiovascular diseases. Nutrients. 2017;9(6):598. https://doi.org/10.3390/nu9060598
5. Khefifi H, Tadeo FR, Selmane R, Ben‐Mimoun M, Morillon R, Luro F. Effect of environment on citrus fruit abscission and maturation. Acta Hortic. 2014;1119:59-64. https://doi.org/10.17660/ActaHortic.2016.1119.8
6. Singh K, Kumar S, Pradhan S, Patidar OP. Organic farming for sustainable and nutritional fruit production in India: A review. Int J Curr Microbiol App Sci. 2018;7(5):3033-9. https://doi.org/10.20546/ijcmas.2018.705.354
7. Kader AA, Yahia E. Postharvest biology of tropical and subtropical fruits. In: Postharvest biology and technology of tropical and subtropical fruits. Elsevier. 2011:79-111. https://doi.org/10.1533/9780857093622.79
8. Sharma S. Heat stress effects in fruit crops: A review. Agric Rev. 2020;41(1):73-8. https://doi.org/10.18805/ag.R-1951
9. Goswami AK, Maurya NK, Goswami S, Bardhan K, Singh SK, Prakash J, et al. Physio-biochemical and molecular stress regulators and their crosstalk for low-temperature stress responses in fruit crops: A review. Front Plant Sci. 2022;13:1022167. https://doi.org/10.3389/fpls.2022.1022167
10. Duarte-Sierra A, Tiznado-Hernández ME, Jha DK, Janmeja N, Arul J. Abiotic stress hormesis: An approach to maintain quality, extend storability and enhance phytochemicals on fresh produce during postharvest. Compr Rev Food Sci Food Saf. 2020;19(6):3659-82. https://doi.org/10.1111/1541-4337.12628
11. Varshney RK, Bansal KC, Aggarwal PK, Datta SK, Craufurd PQ. Agricultural biotechnology for crop improvement in a variable climate: hope or hype? Trends Plant Sci. 2011;16(7):363-71. https://doi.org/10.1016/j.tplants.2011.03.004
12. Corsi S, Ruggeri G, Zamboni A, Bhakti P, Espen L, Ferrante A, et al. A bibliometric analysis of the scientific literature on biostimulants. Agronomy. 2022;12(6):1257. https://doi.org/10.3390/agronomy12061257
13. Farruggia D, Di Miceli G, Licata M, Leto C, Salamone F, Novak J. Foliar application of various biostimulants produces contrasting response on yield, essential oil and chemical properties of organically grown sage (*Salvia officinalis* L.). Front Plant Sci. 2024;15:1397489. https://doi.org/10.3389/fpls.2024.1397489
14. Nardi S, Schiavon M, Francioso O. Chemical structure and biological activity of humic substances define their role as plant growth promoters. Molecules. 2021;26(8):2256. https://doi.org/10.3390/molecules26082256
15. Singh M, Subahan GM, Sharma S, Singh G, Sharma N, Sharma U, et al. Enhancing horticultural sustainability in the face of climate change: Harnessing biostimulants for environmental stress alleviation in crops. Stresses. 2025;5(1):23. https://doi.org/10.3390/stresses5010023
16. Gutiérrez-Rodríguez AG, Juarez-Portilla C, Olivares-Banuelos T, Zepeda RC. Anticancer activity of seaweeds. Drug Discov Today. 2018;23(2):434-47. https://doi.org/10.1016/j.drudis.2017.10.019
17. Xie C, Lee ZJ, Ye S, Barrow CJ, Dunshea FR, Suleria HA. A review on seaweeds and seaweed-derived polysaccharides: Nutrition, chemistry, bioactivities and applications. Food Rev Int. 2024;40(5):1312-47. https://doi.org/10.1080/87559129.2023.2212055
18. El-Beltagi HS, Mohamed AA, Mohamed HI, Ramadan KM, Barqawi AA, Mansour AT. Phytochemical and potential properties of seaweeds and their recent applications: A review. Mar Drugs. 2022;20(6):342. https://doi.org/10.3390/md20060342
19. Mahadevan K. Seaweeds: a sustainable food source. In: Seaweed sustainability. Elsevier. 2015:347-64. https://doi.org/10.1016/B978-0-12-418697-2.00013-1
20. Kılınç B, Cirik S, Turan G, Tekogul H, Koru E. Seaweeds for food and industrial applications. In: Valdez B, editor. Food industry. London: IntechOpen; 2013. https://doi.org/10.5772/53172
21. Shelar‐PS, Reddy‐S, Shelar‐GS, Kavitha‐M, Kumar‐GP, Reddy‐G. Medicinal value of seaweeds and its applications: a review. Continental J Pharmacol Toxicol Res. 2012;5(2):1-22.
22. Morais T, Cotas J, Pacheco D, Pereira L. Seaweeds compounds: an ecosustainable source of cosmetic ingredients? Cosmetics. 2021;8(1):8. https://doi.org/10.3390/cosmetics8010008
23. Fleurence J. Seaweeds as food. Seaweed Health Dis Prev. 2016:149-67. https://doi.org/10.1016/B978-0-12-802772-1.000 05-1
24. Hentati F, Tounsi L, Djomdi D, Pierre G, Delattre C, Ursu AV, et al. Bioactive polysaccharides from seaweeds. Molecules. 2020;25(14):3152. https://doi.org/10.3390/molecules25143152
25. Fleurence J, Morançais M, Dumay J. Seaweed proteins. In: Proteins in food processing. Elsevier. 2018:245-62. https://doi.org/10.1016/B978-0-08-100722-8.00010-3
26. Ruban P, Govindasamy C. Seaweed fertilizers in modern agriculture. Seaweed Fertil Mod Agric. 2018;14(1):4.
27. Arumugam N, Chelliapan S, Kamyab H, Thirugnana S, Othman N, Nasri NS. Treatment of wastewater using seaweed: a review. Int J Environ Res Public Health. 2018;15(12):2851. https://doi.org/10.3390/ijerph15122851
28. Makkar HP, Tran G, Heuzé V, Giger-Reverdin S, Lessire M, Lebas F, et al. Seaweeds for livestock diets: A review. Anim Feed Sci Technol. 2016;212:1-17. https://doi.org/10.1016/j.anifeedsci.2015.09.018
29. Vatsos IN, Rebours C. Seaweed extracts as antimicrobial agents in aquaculture. J Appl Phycol. 2015;27:2017-35. https://doi.org/10.1007/

s10811-014-0506-0

30. Bedoux G, Hardouin K, Burlot AS, Bourgougnon N. Bioactive components from seaweeds: Cosmetic applications and future development. In: Advances in botanical research. Elsevier. 2014:345-78. https://doi.org/10.1016/B978-0-12-408062-1.00012-3
31. Rengasamy KR, Mahomoodally MF, Aumeeruddy MZ, Zengin G, Xiao J, Kim DH. Bioactive compounds in seaweeds: An overview of their biological properties and safety. Food Chem Toxicol. 2020;135:111013. https://doi.org/10.1016/j.fct.2019.111013
32. Prasad K. Symbiotic endophytes of glomalin AM fungi, rhizobium and PGPR potential bio stimulants to intensive global food production for sustainable agriculture system. J Microbes Res. 2023;2(2):2836-187. https://doi.org/10.58489/2836-2187/012
33. Tandel KV, Joshi NH, Tandel GM, Patel M, Tandel JT. Seaweed cultivation in India, a new opportunity of revenue generation. Adv Life Sci. 2016;5(7):2487-91.
34. Milton RF. Liquid seaweed as a fertilizer. Proc Int Seaweed Symp. 1964;4:428-31.
35. Kocira S, Szparaga A, Hara P, Treder K, Findura P, Bartoš P, et al. Biochemical and economical effect of application biostimulants containing seaweed extracts and amino acids as an element of agroecological management of bean cultivation. Sci Rep. 2020;10(1):17759. https://doi.org/10.1038/s41598-020-74959-0
36. Dulanlebit YH, Hernani H. Overview of extraction methods for extracting seaweed and its applications. J Penelit Pendidik IPA. 2023;9(2):817-24. https://doi.org/10.29303/jppipa.v9i2.3053
37. Gullón B, Gagaoua M, Barba FJ, Gullón P, Zhang W, Lorenzo JM. Seaweeds as promising resource of bioactive compounds: Overview of novel extraction strategies and design of tailored meat products. Trends Food Sci Technol. 2020;100:1-18. https://doi.org/10.1016/j.tifs.2020.03.039
38. Godlewska K, Michalak I, Tuhy Ł, Chojnacka K. Plant growth biostimulants based on different methods of seaweed extraction with water. BioMed Res Int. 2016;2016(1):5973760. https://doi.org/10.1155/2016/5973760
39. Premarathna AD, Tuvikene R, Fernando P, Adhikari R, Perera M, Ranahewa T, et al. Comparative analysis of proximate compositions, mineral and functional chemical groups of 15 different seaweed species. Sci Rep. 2022;12(1):19610. https://doi.org/10.1038/s41598-022-23609-8
40. Kristanto FP, Machmudah S, Winardi S, Wahyudiono W, Goto M. Yield and extraction rate analysis of phytochemical compounds from *Eucheuma cottonii*, *Ganoderma lucidum* and *Gracilaria* sp. using subcritical water extraction. ASEAN J Chem Eng. 2021;21(1):27-37. https://doi.org/10.22146/ajche.60513
41. Cotas J, Leandro A, Monteiro P, Pacheco D, Figueirinha A, Gonçalves AM, et al. Seaweed phenolics: From extraction to applications. Mar Drugs. 2020;18(8):384. https://doi.org/10.3390/md18080384
42. Khalil H, Lai T, Tye Y, Rizal S, Chong E, Yap S, et al. A review of extractions of seaweed hydrocolloids: Properties and applications. Express Polym Lett. 2018;12(4). https://doi.org/10.3144/expresspolymlett.2018.27
43. Wolle MM, Conklin SD. Speciation analysis of arsenic in seafood and seaweed: part I-evaluation and optimization of methods. Anal Bioanal Chem. 2018;410(22):5675-87. https://doi.org/10.1007/s00216-018-0906-0
44. Jacobsen C, Sørensen ADM, Holdt SL, Akoh CC, Hermund DB. Source, extraction, characterization and applications of novel antioxidants from seaweed. Annu Rev Food Sci Technol. 2019;10(1):541-68. https://doi.org/10.1146/annurev-food-032818-121401
45. Sanagi MM, Loh SH, Wan Ibrahim WN, Pourmand N, Salisu A, Wan Ibrahim WA, et al. Agarose-and alginate-based biopolymers for sample preparation: Excellent green extraction tools for this century. J Sep Sci. 2016;39(6):1152-9. https://doi.org/10.1002/jssc.201501207
46. Grosso C, Valentão P, Ferreres F, Andrade PB. Alternative and efficient extraction methods for marine-derived compounds. Mar Drugs. 2015;13(5):3182-230. https://doi.org/10.3390/md13053182
47. Vijayan SR, Santhiyagu P, Singamuthu M, Kumari Ahila N, Jayaraman R, Ethiraj K. Synthesis and characterization of silver and gold nanoparticles using aqueous extract of seaweed, *Turbinaria conoides* and their antimicrofouling activity. Sci World J. 2014;2014(1):938272. https://doi.org/10.1155/2014/938272
48. Lim SJ, Chang LS, Fazry S, Mustapha WAW, Babji AS. Functional food & ingredients from seaweed, edible bird's nest and tropical fruits: a translational research. LWT. 2021;151:112164. https://doi.org/10.1016/j.lwt.2021.112164
49. Anderson R, Bolton J, Stegenga H. Using the biogeographical distribution and diversity of seaweed species to test the efficacy of marine protected areas in the warm-temperate Agulhas Marine Province, South Africa. Divers Distrib. 2009;15(6):1017-27. https://doi.org/10.1111/j.1472-4642.2009.00614.x
50. Al-Shatri A, Pakyürek M, Yavic A. Effect of seaweed application on the vegetative growth of strawberry cv. Albion grown under Iraq ecological conditions. Appl Ecol Environ Res. 2020;18(1). https://doi.org/10.15666/aeer/1801_12111225
51. Haider MW, Ayyub CM, Pervez MA, Asad HU, Manan A, Raza SA, et al. Impact of foliar application of seaweed extract on growth, yield and quality of potato (*Solanum tuberosum* L.). Soil Environ. 2012;31(2).
52. Al-Taee R, Al-Juthry H, Al-Badrani W. Effect of inoculation of mycorrhizae, sprayed of nanoseaweeds extract and nano specific fertilizer on growth and yield of wheat. Plant Cell Biotechnol Mol Biol. 2020:35-43.
53. Aljaberi MA, Altai DS, Ubaid MK, Alhasany A. Response of barley to nano-feeding with seaweed extract and bio-fertilizer. J Glob Innov Agric Sci. 2023;11:199-203. https://doi.org/10.22194/JGIAS/23.1052
54. Verkleij F. Seaweed extracts in agriculture and horticulture: a review. Biol Agric Hortic. 1992;8(4):309-24. https://doi.org/10.1080/01448765.1992.9754608
55. Crouch I, Van Staden J. Evidence for rooting factors in a seaweed concentrate prepared from *Ecklonia maxima*. J Plant Physiol. 1991;137(3):319-22. https://doi.org/10.1016/S0176-1617(11)80138-0
56. Lüthje S, Böttger M. On the function of a K-type vitamin in plasma membranes of maize (*Zea mays* L.) roots. Mitt Inst Allg Bot Univ Hamburg. 1995;25:5-13.
57. Castaings L, Marchive C, Meyer C, Krapp A. Nitrogen signalling in *Arabidopsis*: how to obtain insights into a complex signalling network. J Exp Bot. 2011;62(4):1391-7. https://doi.org/10.1093/jxb/erq375
58. Khan W, Hiltz D, Critchley AT, Prithiviraj B. Bioassay to detect *Ascophyllum nodosum* extract-induced cytokinin-like activity in *Arabidopsis thaliana*. J Appl Phycol. 2011;23:409-14. https://doi.org/10.1007/s10811-010-9583-x
59. Turan M, Köse C. Seaweed extracts improve copper uptake of grapevine. Acta Agric Scand Sect B-Soil Plant Sci. 2004;54(4):213-20. https://doi.org/10.1080/09064710410030311
60. Crouch I, Beckett R, Van Staden J. Effect of seaweed concentrate on the growth and mineral nutrition of nutrient-stressed lettuce. J Appl Phycol. 1990;2:269-72. https://doi.org/10.1007/BF02179784
61. Dobromilska R, Mikiciuk M, Gubarewicz K. Evaluation of cherry tomato yielding and fruit mineral composition after using of Bio-algeen S-90 preparation. J Elem. 2008;13(4):491-9.
62. Blunden G. Agricultural uses of seaweeds and seaweed products. In: Guiry MD, Blunden G, editors. Seaweed resources in Europe: uses and potential. Chichester: John Wiley & Sons. 1991:65-81.
63. Khan A, Munir M, Shaheen T, Tassawar T, Rafiq M, Ali S, et al. Supplemental foliar applied mixture of amino acids and seaweed extract improved vegetative growth, yield and quality of citrus fruit. Sci Hortic. 2022;296:110903. https://doi.org/10.1016/j.scienta.2022.110903
64. Pavlou A, Efstathiou E, Christodoulou S, Stylianou S, Manganaris GA. The effect of preharvest applications with biostimulants on

qualitative properties and postharvest performance of loquat fruit. Acta Hortic. 2022;1344:129-36. https://doi.org/10.17660/ActaHortic.2022.1344.20

65. Cirillo A, Izzo L, Ciervo A, Ledenko I, Cepparulo M, Piscitelli A, et al. Optimizing apricot yield and quality with biostimulant interventions: A comprehensive analysis. Horticulturae. 2024;10(5):447. https://doi.org/10.3390/horticulturae10050447

66. Spann TM, Little HA. Applications of a commercial extract of the brown seaweed *Ascophyllum nodosum* increases drought tolerance in container-grown 'Hamlin' sweet orange nursery trees. HortScience. 2011;46(4):577-82. https://doi.org/10.21273/HORTSCI.46.4.577

67. Frioni T, Sabbatini P, Tombesi S, Norrie J, Poni S, Gatti M, et al. Effects of a biostimulant derived from the brown seaweed *Ascophyllum nodosum* on ripening dynamics and fruit quality of grapevines. Sci Hortic. 2018;232:97-106. https://doi.org/10.1016/j.scienta.2017.12.054

68. Abo-Zaid FS, Zagzog OA, El-Nagar NI, Qaoud E. Effect of sea weed and amino acid on fruiting of some grapevine cultivars. J Product Dev. 2019;24(3):677-703. https://doi.org/10.21608/jpd.2019.48176

69. Gutiérrez-Gamboa G, Garde-Cerdán T, Souza-Da Costa B, Moreno-Simunovic Y. Strategies for the improvement of fruit set in *Vitis vinifera* L. cv. 'Carménère' through different foliar biostimulants in two different locations. Ciênc E Téc Vitivinícola. 2018;33(2):177-83. https://doi.org/10.1051/ctv/20183302177

70. Basak A. Effect of preharvest treatment with seaweed products, Kelpak® and Goëmar BM 86®, on fruit quality in apple. Int J Fruit Sci. 2008;8(1-2):1-14. https://doi.org/10.1080/15538360802365251

71. Belal BES, El-Kenawy MA, El-Mogy S, Mostafa Omar AS. Influence of arbuscular mycorrhizal fungi, seaweed extract and nano-zinc oxide particles on vegetative growth, yield and clusters quality of 'Early Sweet' grapevines. Egypt J Hortic. 2023;50(1):1-16. https://doi.org/10.21608/ejoh.2022.167481.1217

72. Ismaiel HM, Ismail HS. Effect of spraying some amino acids and seaweed extract on the yield and quality fruits of Valencia orange. Egypt J Hortic. 2024;51(2):151-60. https://doi.org/10.21608/ejoh.2023.213742.1248

73. Monteiro E, Baltazar M, Pereira S, Correia S, Ferreira H, Alves F, et al. *Ascophyllum nodosum* extract and glycine betaine preharvest application in grapevine: enhancement of berry quality, phytochemical content and antioxidant properties. Antioxidants. 2023;12(10):1835. https://doi.org/10.3390/antiox12101835

74. Sabry GH, Rizk-Alla MS, Abd El-Wahab M. Influence of effective micro-organisms, seaweed extract and amino acids application on growth, yield and bunch quality of Red globe grapevines. J Plant Prod. 2009;34(6):6617-37. https://doi.org/10.21608/jpp.2009.118638

75. Popescu GC, Popescu M. Effect of the brown alga *Ascophyllum nodosum* as biofertilizer on vegetative growth in grapevine (*Vitis vinifera* L.). Curr Trends Nat Sci. 2014;3:61-7.

76. Kök D. Effects of foliar seaweed and humic acid treatments on monoterpene profile and biochemical properties of cv. Riesling berry (*V. vinifera* L.) throughout the maturation period. J Tekirdag Agric Fac. 2016;13(2):67-74.

77. Masoud AA, Mohamed AK, AbouZaid IA, Abd El-Hakim MH. Effect of foliar application with some natural and chemical compounds on yield of Ruby Seedless grape cultivar. Assiut J Agric Sci. 2023;54(1):198-212. https://doi.org/10.21608/ajas.2023.173439.1198

78. El-Senosy O. Effect of chitosan and seaweed extracts on fruiting of flame seedless grapevines grown under sandy soil condition. Int J Mod Agric Environ. 2022;2(1):24-32. https://doi.org/10.21608/ijmae.2022.296351

79. Ahmed A. The application of some biostimulant-based substances to improve the quality and productivity of "Ruby Seedless" grapevines cv. Middle East J Agric Res. 2022;11(1):304-11.

80. Al-Saif AM, Sas-Paszt L, Awad RM, Mosa WF. Apricot (*Prunus armeniaca*) performance under foliar application of humic acid, brassinosteroids and seaweed extract. Horticulturae. 2023;9(4):519. https://doi.org/10.3390/horticulturae9040519

81. Li J, Brecht JK, Kim J, Bailey LS, Kamat MN, Basso KB, et al. Seaweed extract and microbial biostimulants show synergistic effects on improving organic strawberry production. HortScience. 2024;59(8):1114-26. https://doi.org/10.21273/HORTSCI17647-23

82. Bajpai S, Shukla PS, Asiedu S, Pruski K, Prithiviraj B. A biostimulant preparation of brown seaweed *Ascophyllum nodosum* suppresses powdery mildew of strawberry. Plant Pathol J. 2019;35(5):406. https://doi.org/10.5423/PPJ.OA.03.2019.0066

83. Soppelsa S, Kelderer M, Casera C, Bassi M, Robatscher P, Andreotti C. Use of biostimulants for organic apple production: Effects on tree growth, yield, and fruit quality at harvest and during storage. Front Plant Sci. 2018;9:1342. https://doi.org/10.3389/fpls.2018.01342

84. Patel D, Ahlawat T, Pandey A, Jena S. Improved fruit quality in papaya cv. Red Lady though foliar sprays of silicon and seaweed extract. J Pharma Innov. 2021;10(5):1514-6.

85. Harhash MM, Shama SM, Ghazal KF. Effect of spraying moringa, seaweed extract and potassium on yield and fruit quality of the winter guava 'Maamoura' cultivar. J Adv Agric Res. 2019;24(1):132-45.

86. Abdel-Sattar M, Al-Obeed RS, Makhasha E, Mostafa LY, Abdelzaher RA, Rihan HZ. Improving mangoes' productivity and crop water productivity by 24-epibrassinosteroids and hydrogen peroxide under deficit irrigation. Agric Water Manag. 2024;298:108860. https://doi.org/10.1016/j.agwat.2024.108860

87. Arioli T, Mattner SW, Hepworth G, McClintock D, McClinock R. Effect of seaweed extract application on wine grape yield in Australia. J Appl Phycol. 2021;33(3):1883-91. https://doi.org/10.1007/s10811-021-02423-1

88. Ravi I, Kamaraju K, Kumar S, Nori SS. Foliar application of seaweed bio formulation enhances growth and yield of banana cv. Grand Naine (AAA). Indian J Nat Sci. 2018;8:13482-8.

89. Al-Rawi W, Al-Hadethi M, Abdul-Kareem A. Effect of foliar application of gibberellic acid and seaweed extract spray on growth and leaf mineral content on peach trees. Iraqi J Agric Sci. 2016;47(1). https://doi.org/10.36103/ijas.v47i3.564

90. Spinelli F, Fiori G, Noferini M, Sprocatti M, Costa G. Perspectives on the use of a seaweed extract to moderate the negative effects of alternate bearing in apple trees. J Hortic Sci Biotechnol. 2009;84(6):131-7. https://doi.org/10.1080/14620316.2009.11512610

91. Spinelli F, Fiori G, Noferini M, Sprocatti M, Costa G. A novel type of seaweed extract as a natural alternative to the use of iron chelates in strawberry production. Sci Hortic. 2010;125(3):263-9. https://doi.org/10.1016/j.scienta.2010.03.011

92. Ashour M, Al-Souti AS, Hassan SM, Ammar GA, Goda AMS, El-Shenody R, et al. Commercial seaweed liquid extract as strawberry biostimulants and bioethanol production. Life. 2022;13(1):85. https://doi.org/10.3390/life13010085

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.