

Review

Role of Seaweeds for Improving Soil Fertility and Crop Development to Address Global Food Insecurity

Ali Rafi Yasmeen ^{1,†}, Theivanayagam Maharajan ^{2,†} , Ramakrishnan Rameshkumar ³, Subbiah Sindhamani ⁴, Balan Banumathi ⁵, Mayakrishnan Prabakaran ^{6,7} , Sundararajan Atchaya ⁸  and Periyasamy Rathinapriya ^{9,*} 

- ¹ Department of Zoology, Government Arts College, Chennai 600035, India; yasmeenar1998@gmail.com
- ² Division of Plant Molecular Biology and Biotechnology, Department of Biosciences, Rajagiri College of Social Sciences, Cochin 683104, India; susirajan143@gmail.com
- ³ CweedLab Pvt. Ltd., Aymoor, Nagapattinam 614712, India; r.rameshkarthick@gmail.com
- ⁴ Department of Biotechnology, Science Campus, Alagappa University, Karaikudi 603003, India; lakshmansindhu12@gmail.com
- ⁵ Department of Animal Health and Management, Science Campus, Alagappa University, Karaikudi 630003, India; banu.wlb@gmail.com
- ⁶ Institute for Fiber Engineering and Science (IFES), Interdisciplinary Cluster for Cutting Edge Research (ICCER), National University Corporation Shinshu University, Ueda 390-8621, Japan; prabakaranmitt@gmail.com
- ⁷ Department of Biomaterials, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai 600078, India
- ⁸ School of Electrical and Electronics Engineering (SEEE), SASTRA Deemed University, Thanjavur 613401, India; akshayananosci@gmail.com
- ⁹ Horticultural and Herbal Crop Environment Division, National Institute of Horticultural and Herbal Science, Rural Development Administration, Wanju 55365, Republic of Korea
- * Correspondence: rathina.priya25@gmail.com
- † These authors contributed equally to this work.

Abstract: Seaweeds and their derived products have long been valued in organic agriculture, serving roles in biofertilizers, biostimulants, and soil conditioners due to their rich content of bioactive compounds. With increasing concerns over the negative impacts of synthetic agrochemicals on food security and environmental health, seaweeds offer a sustainable alternative for improving soil fertility and crop productivity. This review synthesizes recent findings on the use of seaweeds to enhance soil physicochemical properties, stimulate beneficial microbial activity, and improve nutrient availability. Furthermore, it highlights how seaweed applications can mitigate various abiotic stresses, such as droughts, salinity, and nutrient deficiency, by enhancing antioxidant defenses and promoting physiological and biochemical resilience in plants. Key agronomic benefits include improved seed germination, root development, photosynthesis, biomass accumulation, and yield performance. By acting as natural soil amendments, seaweeds support sustainable soil management and contribute to long-term agricultural resilience. This review emphasizes the urgent need for standardized application strategies and integrated research to unlock the full potential of seaweed-based solutions in sustainable farming systems.

Keywords: seaweed; soil amendment; sustainable agriculture; abiotic stress; bioactive compounds; biostimulant; crop productivity



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1. Introduction

The “zero hunger” plan is one of the main goals of the “UN 2030 sustainable development” agenda to meet food demands for the growing global population and alleviate

global nutrient deficiency through developing bio-fortified crops [1]. In response to this challenge, farmers resort to using inorganic fertilizers to boost crop production [2]. However, some farmers apply excessive amounts of fertilizers to soil without sufficient knowledge, which reduces soil fertility and poses a threat to the environment. To meet the growing need for food, it is mandatory to manage natural resources better, practice sustainable farming, use low-carbon inputs more efficiently, and make sure plants receive all nutrients adequately. Apart from being an excellent source of nutritious food, seaweeds can be used as biofertilizers or biostimulants, a potential alternative to achieve greater agricultural production [3–5]. The global seaweed production reached 36.3 million tons in 2021, with increasing use in agriculture [6]. In addition, according to FAO 2006, earlier statistics stated ~15 million metric tons per annum of seaweeds utilized as biostimulants for crop cultivation [7]. Recently, the seaweed biostimulant market, valued at CAGR 12.9% in 2023, is projected to reach USD 2581.48 M by 2030 [8]. The US and EU also include biostimulants in fertilizer regulations, and the official gazette of India incorporated phycobiostimulants, i.e., seaweed-derived biostimulants in regulatory frameworks [9,10].

The worldwide population rate will reach 8.5 billion in 2030 and is projected to increase to 10.4 billion in the 2080s, with the main global risk of hunger in feeding over billions of inhabitants in the future [11]. Seaweeds are primitive, photosynthetic non-blooming macrophytes, with renewable sources from nature. About 10,000 wide varieties of seaweed species have been reported globally [12]. The “weed” in seaweed is surely not a wild, unwanted growth or a pest in the marine environment. Apart from being an excellent source of nutritious food, seaweeds can be used as biostimulants and biofertilizers and in biochar and biofuel production. In marine ecosystems, seaweeds play a significant biological and ecofriendly role by maintaining their stability [13]. Seaweeds afford reproduction, nutrition supply, and an accommodating environment for other marine organisms. As a producer, some seaweeds float on the water surface with single or multicellular colonies [14].

Seaweeds are diverse in nature, colorful, and ornamental with varied structures. *Rhodophyceae* (red), *Chlorophyceae* (green), and *Phaeophyceae* (brown) are the three main groups of seaweeds. They are high in vitamins, minerals, omega-3 fatty acids, and many other macro- and micronutrients [15]. Seaweeds are reported to have high levels of sodium, potassium, calcium, magnesium, and phosphorus, along with trace elements, like iron, manganese, copper, zinc, cobalt, and selenium, which are also rich in soluble fibers and iodine [15,16]. The most commonly consumed seaweeds are *Porphyra* sp., *Undaria* sp., *Saccharina* sp., and *Palmaria* sp., containing rich sources of proteins [17]. Even though seaweed has been the subject of many studies, there has been a great need for up-to-date literature reviews that explain how they might be used as soil amendments instead of inorganic chemical fertilizers. Therefore, the aim of the present review is to provide a comprehensive overview of the potential value of several seaweeds and their effects on green agriculture supplementation and antioxidant activity for a significant contribution to the development of novel biofertilizers for sustainable crop improvement. This review article was developed based on available sources from Google Scholar, Web of Sciences, and Scopus.

2. Role of Bioactive Compounds Extracted from Seaweeds for Crop Improvement

Seaweeds are rich in bioactive compounds, including polysaccharides, proteins, lipids, vitamins, minerals, phenolic compounds, and pigments, which significantly contribute to soil health and crop productivity [Figure 1] [18]. These chemicals improve the structure of the soil, the activity of microbes, and the availability of nutrients. This advantage makes seaweed-based amendments a beneficial and long-lasting alternative to synthetic

fertilizers. Polysaccharides, such as alginate, fucoidan, carrageenan, and ulvan, improve soil aggregation, aeration, and moisture retention, particularly in sandy and degraded soils [19]. Brown seaweeds (*Ascophyllum nodosum*, *Sargassum*, and *Laminaria digitata*) contain high concentrations of alginate and fucoidan, which promote soil stability and water retention [18,20]. A lot of sulfated polysaccharides, like agar and carrageenan, are found in red seaweeds like *Gracilaria*, *K. alvarezii*, and *Chondrus crispus* [21]. These help the plants hold on to water and combine with phosphorus and trace elements. Green seaweeds like *Ulva lactuca* and *Enteromorpha* break down quickly, giving the environment a quick source of organic matter that increases the number of microbes and enzymes that are active [22]. Seaweeds also have macro- and micronutrients, like potassium, calcium, manganese, iron, zinc and copper, that improve nutrient bioavailability and increase the cation exchange capacity [16]. This makes sure that essential minerals are always available. Also, phenolic compounds like phlorotannins and flavonoids are antimicrobial, which means they kill soil-borne pathogens and encourage the growth of beneficial soil microorganisms, such as *rhizobium*, *azotobacter*, and mycorrhizae, which support nutrient cycling, plant growth, and disease suppression [23]. Because seaweeds contain chlorophyll, carotenoids, and phycobiliproteins, they help soil microbes respire and store carbon, which helps the soil grow back and nutrients move around.

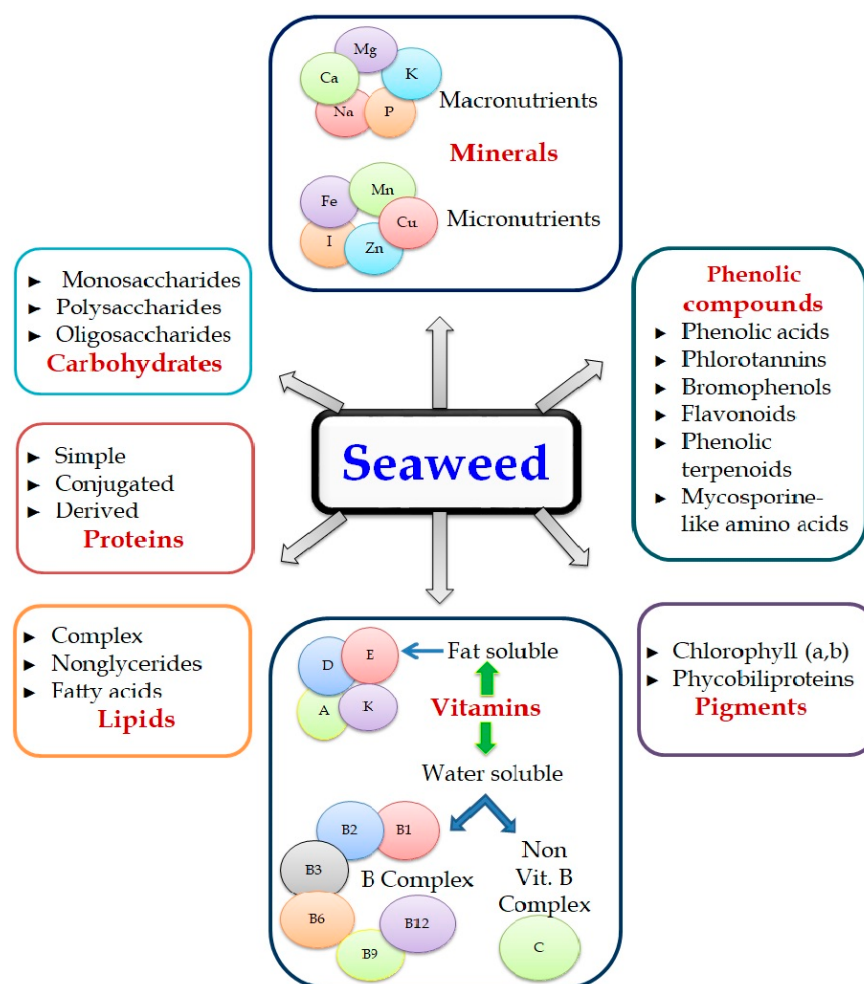


Figure 1. Reported bioactive compounds of seaweeds.

Adding seaweed-based amendments to farmland has many benefits for both farming and the environment. These benefits include better soil structures, more diverse microbes, better water retention, and less need for chemical inputs [24]. Furthermore, seaweed-

derived phenolic compounds and antimicrobial agents help control soil-borne diseases, reducing the need for synthetic pesticides and fungicides [25]. In addition, bioactive compounds found in seaweed help store carbon and make humus, which helps the soil accumulate organic matter and stay fertile over time [19]. In terms of improving crops, seaweed extracts work as biostimulants to help seeds sprout and roots grow and to help plants absorb nutrients better and handle stress better [26]. Plant growth regulators, such as cytokinins, auxins, and gibberellins, help plants flower, fruit, and grow stronger overall, which results in higher crop yields and better quality [27]. The lipids and fatty acids in seaweeds help the roots interact with the soil, which makes it easier for plants to take in water and grow in bad conditions, like droughts and high salt levels [28]. Given their multifunctional benefits, seaweed-based amendments represent a sustainable solution for enhancing both soil fertility and agricultural productivity. However, although it is well known that they can improve soil and crops, more research needs to be conducted to find the best ways to process them, set standard rates for applications, and address any concerns about salt buildup and heavy metal accumulation. As the agricultural sector transitions toward eco-friendly and climate-resilient farming practices, the utilization of seaweed-derived bioactive compounds in soil management offers a promising approach to ensuring long-term soil health and sustainable food production.

3. Impact of Seaweeds on Soil Health

Soil health is a fundamental component of sustainable agriculture, influencing nutrient cycling, water retention, microbial diversity, and overall soil productivity. Among various organic amendments, seaweed-derived materials have been widely recognized for their ability to enhance soil structure, chemical composition, and biological activity [29]. Using seaweeds in different forms, like composts, liquid extracts, powders, or granules, has shown to make soil much more fertile and resilient [30]. This makes them a long-term alternative to synthetic fertilizers and soil conditioners. Because they have a lot of alginate, fucoidan, laminarin, and mannitol, brown seaweeds, like *A. nodosum*, *Fucus vesiculosus*, *Laminaria digitata*, and *Sargassum* sp., are used a lot in farming [31]. All of these play a crucial role in soil aggregation, improving the soil structure and water-holding capacity. Alginate, in particular, forms a gel-like matrix when applied to the soil, increasing soil porosity and aeration, which in turn enhances root penetration and microbial activity [32].

In terms of chemical properties, brown seaweeds are rich in potassium, calcium, magnesium, and trace elements, which contribute to improved CEC in soil [30]. Increased CEC allows for the better retention and exchange of essential nutrients, reducing leaching losses and improving soil fertility [33]. Additionally, brown seaweeds influence soil pH regulation through their humic and fulvic acid content, preventing extreme pH fluctuations that could negatively impact microbial life and nutrient availability [34].

The rich organic matter in brown seaweeds also helps soil microorganisms do their job, which includes creating beneficial microorganisms that assist with disease control and nutrient cycling. When brown seaweeds are added to compost or mulch, they speed up the breakdown of organic matter, which helps the soil form stable aggregates and stops soil erosion [35]. It is important to think about the salinity risks that come with using too much brown seaweed, because some species have a lot of sodium, which can affect the structure of the soil and make it harder for water to get in [36].

Red seaweeds, including *Chondrus crispus* (Irish moss), *Gracilaria*, *K. alvarezii*, and *Gelidium*, are primarily valued for their high content of carrageenan and agar, which improve the soil texture and moisture retention [37]. These sulfated polysaccharides act as natural binding agents, helping soil particles form aggregates that enhance structural stability and aeration. Red seaweeds also contain complexing compounds, such as amino acids and

sugars, which increase the nutrient retention capacity and prevent nutrient leaching [38]. These compounds improve the bioavailability of essential nutrients, particularly phosphorus, which is often immobilized in the soil and unavailable to plants [39]. Additionally, they stimulate soil microbial populations, particularly beneficial bacteria and fungi involved in organic matter decomposition and humus formation [19]. A key benefit of red seaweeds in soil amendment is their ability to buffer soil pH fluctuations through their humified organic matter [35]. This effect stabilizes the soil environment, reducing the risks associated with sudden acidification or alkalization, which could negatively impact nutrient availability and microbial survival. Furthermore, red seaweeds reduce soil compaction, making them particularly useful in heavy clay soils that suffer from poor drainage and aeration.

Green seaweeds, such as *U. lactuca* (sea lettuce), *Enteromorpha*, and *Codium fragile*, are often overlooked in soil improvement but offer substantial benefits due to their high nitrogen content, rapid decomposition, and ability to remediate soil contaminants [40]. Unlike brown and red seaweeds, green seaweeds have a higher decomposition rate, making them an excellent source of quick-release organic matter that enhances the microbial biomass and enzyme activity in the soil [41]. One of the most important roles of green seaweeds in soil health is bioremediation [40]. These macroalgae have a high capacity for absorbing heavy metals and pollutants, making them effective for detoxifying contaminated soils [42]. The high cellulose and ulvan content in green seaweeds also supports soil aggregation and the water holding capacity, reducing soil erosion and improving resilience against drought conditions [19]. Another crucial function of green seaweeds is their ability to enhance CEC due to their colloidal properties [43]. By forming ionic complexes with soil particles, green seaweed extracts improve nutrient retention and slow nutrient leaching, ensuring a steady supply of essential minerals to the soil ecosystem.

Each type of seaweed contributes differently to soil health depending on its biochemical composition and mode of application. Brown seaweeds excel in improving soil structure and moisture retention, red seaweeds contribute to nutrient retention and pH buffering, and green seaweeds play a crucial role in bioremediation and quick organic matter decomposition. However, largescale applications must consider potential risks, such as the high sodium content in certain species (e.g., *Sargassum*), the possibility of heavy metal accumulation, and the need for proper composting or processing to avoid introducing unwanted contaminants into the soil.

4. Effects of Seaweeds on Plant Growth and Stress Tolerance

Agriculture is the prime source of livelihoods in India, and the estimated total food grain production was ~275 million tons [44]. Today, India is the largest global producer (25%), consumer (27% of world consumption), and importer (14%) of important pulses in the universe [45]. Agriculture provides the large size of wage goods and raw materials to nonagricultural and industrial sectors. Today, India ranks 2nd in worldwide farm output, and USD 39 billion of agricultural commodities were exported in 2013, making it the 6th largest net exporter and 7th largest worldwide agricultural exporter [46]. Seaweeds are macroscopic benthic marine macroalgae and are photoautotrophic; biodegradable; ecofriendly; nonpolluting; nontoxic; and nonhazardous to fauna, flora, and humans [47,48]. In India, an enormous distribution of seaweeds was found in the Southern coastal region, and approximately 200 different species have been identified and are used as biomanure and compost in coastal agriculture [49,50]. FAO 2022 data suggest that 35.8 million tons of seaweeds and other marine plant species were produced in 2019 [51]. This substantial production forms a vital part of the global Blue Economy, which generates approximately USD 2.5 trillion annually and supports millions of livelihoods worldwide [52].

There are higher amounts of endogenous macronutrients, micronutrients, organic acids, vitamins, auxins, cytokinins, gibberellins, and amino acids in seaweed extracts that help the growth and yields of many types of plants [47,53,54]. Seaweeds, an organic biostimulant, promote the growth, development, and productivity of plants through high nutritional compositions. Seaweeds are used in green agriculture technology as a foliar spray and conditioner to improve the nutrients in the soil and the rate at which plant cells divide. This technique makes crops grow faster, produce more, and be more productive [55]. The nutrients present in seaweeds can help maintain the moisture content in the soil [28]. Seaweeds are rich in growth regulators, like auxin, abscisic acid, cytokinins, and gibberellins, along with micro- and macronutrients, carbohydrates, vitamins, and minerals, which are plant growth stimulators that aid in the overall crop growth and yields [56]. Biostimulants or biofertilizers made from seaweed help cells grow and plants' metabolisms work better throughout their lives [57]. Seaweed supplements enrich shoot and root growth, thus augmenting the fresh and dry weight of treated plants [58,59]. Scientists have looked at how seaweeds can help with the technical side of farming in a number of different food crops, as well as horticultural, biofuel, flower, and ornamental crops [60,61]. As we move toward more sustainable farming methods, seaweed can be used to improve leaf quality, root growth, seed priming, and crop yields [Figure 2]. Furthermore, seaweeds produce resistance against various abiotic and biotic stressors [62,63].

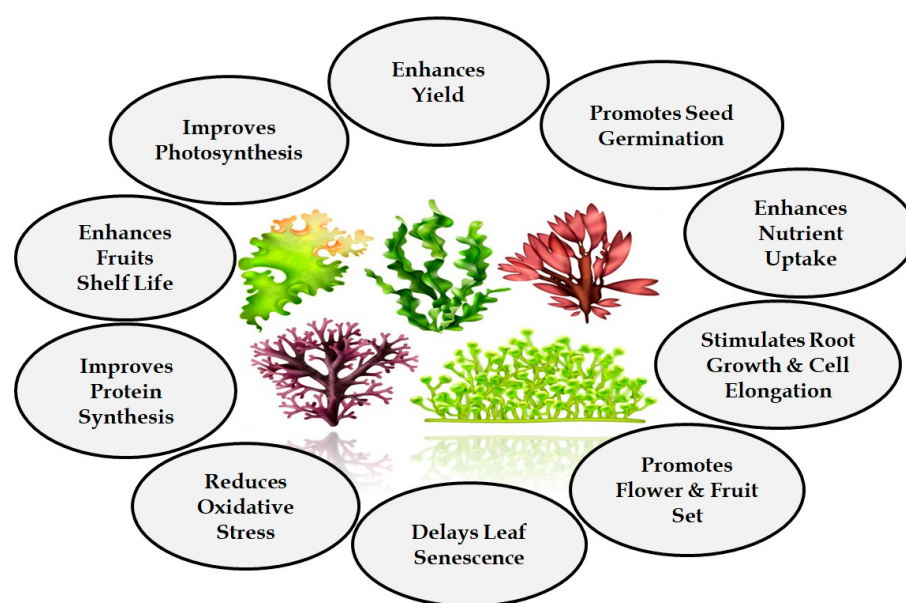


Figure 2. Effects of seaweeds on plant growth and development.

Many research studies have shown that seaweed extract improves the growth of cowpeas, the germination of seeds, and the development of shoots into roots. It also increases the yields of crops like maize [64], rice [65], wheat [66], and other crops (Table 1). Table 1 shows the different types of seaweed extracts and their role in plant growth, development, and yield enhancement. Researchers have found that the green seaweed *Gracilaria edulis* enhances the yields of green gram, wheat, rice, and sweet corn [65–68]. Plants treated with seaweed extracts significantly improve bioactive contents, like flavonoids and phenols, and soluble proteins also ameliorate antioxidant activity [69]. An earlier study found that *Caulerpa scalpelliformis* extract improves plants' biochemical makeup and vegetative growth [70]. Rathinapriya et al. (2020) reported that the biostimulant properties of *Padina boergeresii* and *G. edulis* work together to improve foxtail millet's growth, development, quality, and yield [4]. A number of studies found that plants that were treated with seaweed extract or powder had higher yields of cowpea, wheat, rice, green gram, plum, tomato,

brinjal, sweet corn, and mango. Hence, seaweeds alleviate toxic chemical fertilizers and develop sustainable agriculture practices (Table 1).

Table 1. Applications of seaweed extracts in crop improvement.

Crops	Seaweeds Used	Effects	References
<i>B. vulgaris</i>	<i>E. maxima</i>	Growth improvement	[71]
<i>T. aestivum</i>	<i>E. maxima</i>	Growth and yield improvement	[72]
	<i>S. wightii</i>	Growth and yield improvement	[58]
	<i>K. alvarezii</i> and <i>G. edulis</i>	Yield and quality improvement	[66]
<i>P. pinea</i>	<i>E. maxima</i>	Growth improvement	[73]
<i>B. napus</i>	<i>E. maxima</i>	Yield improvement	[74]
<i>C. annuum</i>	<i>E. maxima</i>	Growth and yield improvement	[75]
<i>A. stolonifera</i>	<i>A. nodosum</i>	Improved physiological activity	[76]
<i>R. mucronata</i>	<i>P. boergesenii</i>	Improvement in germination and growth	[77]
<i>G. max</i>	<i>K. alvarezii</i>	Growth and yield improvement	[78]
<i>P. vulgaris</i>	<i>F. spiralis</i> and <i>U. rigida</i>	Physiological and biochemical improvement	[79]
<i>P. radiata</i>	<i>K. alvarezii</i>	Growth and nutritional level improvement	[80]
<i>A. esculentus</i>	<i>R. intricata</i>	Growth and pigment concentration enhancement	[81]
<i>Cyamopsis tetragonoloba</i>	<i>S. wightii</i> and <i>U. lactuca</i>	Growth, yield, and biochemical property improvement	[82]
<i>A. hypogaea</i>	<i>S. wightii</i> and <i>U. lactuca</i>	Yield improvement	[83]
	<i>S. wightii</i>	Growth, yield, and biochemical property improvement	[84]
<i>V. unguiculata</i>	<i>U. lactuca</i>	Growth improvement	[85]
<i>V. sinensis</i>	<i>S. wightii</i> and <i>C. chemnitzia</i>	Growth and biochemical constituent improvement	[74]
<i>V. mungo</i>	<i>C. scalpelliformis</i>	Growth, yield, and biochemical property improvement	[70]
	<i>U. reticulata</i>	Enhanced chlorophyllase activity, germination, and growth	[86]
	<i>K. alvarezii</i> and <i>G. edulis</i>	Productivity and quality improvement	[87]
<i>V. radiata</i>	<i>S. wightii</i>	Growth and biochemical content improvement	[88]
	<i>Kappaphycus</i> and <i>Gracilaria</i>	Growth and yield improvement	[60]
<i>P. peltatum</i>	<i>E. maxima</i>	Growth, photosynthetic pigment, and phenolic and protein content improvement	[89]
<i>B. napus</i>	<i>A. nodosum</i>	Physiological improvement	[90]
<i>L. esculentum</i>	<i>G. edulis</i> and <i>S. wightii</i>	High-frequency mass propagation and growth improvement	[91]
<i>S. lycopersicum</i>	<i>U. lactuca</i> , <i>C. sertularioides</i> , <i>P. gymnospora</i> , and <i>S. liebmanni</i>	Growth improvement	[47]
<i>S. melongena</i>	<i>G. salicornia</i> , <i>P. gymnospora</i> , <i>P. boergesenii</i> , and <i>G. acerosa</i>	High-frequency mass propagation and growth improvement	[50]
<i>S. oleracea</i>	<i>A. nodosum</i>	Improvement in chlorophyll and ascorbate and lipid peroxidation and postharvest enhancement	[92]
<i>W. somnifera</i>	<i>G. edulis</i> and <i>S. wightii</i>	Productivity improvement	[93]

Table 1. Cont.

Crops	Seaweeds Used	Effects	References
<i>Z. mays</i>	<i>K. alvarezii</i> and <i>G. edulis</i>	Productivity improvement	[94]
	<i>G. edulis</i> and <i>K. alvarezii</i>	Yield and quality improvement	[95]
<i>E. coracana</i>	<i>G. edulis</i> and <i>P. boergeresii</i>	Improvement in plant growth	[96]
<i>O. sativa</i>	<i>K. alvarezii</i> and <i>G. edulis</i>	Productivity improvement	[97]
<i>L. sativa</i>	<i>G. caudata</i> and <i>G. domingensis</i>	Growth improvement	[98]

4.1. Antioxidant Properties of Seaweeds

Free radicals adversely alter proteins, lipids, and DNA, which triggers normal cellular function in plants. Antioxidants play a key role in combating free radical productions and are necessary for proper physiological functions [99]. Antioxidant enzymes, such as superoxide dismutase, ascorbate peroxidase, guaiacol peroxidase, glutathione transferase, and catalase, are mixed in with the enzymatic parts. These enzymes are very important for making cells resistant to abiotic stressors. Environmental stresses induce reactive oxygen species that are detrimental to macromolecules. Hydrogen peroxide, superoxide anion radicals, and singlet oxygen are released during cell signaling proliferation. These radicals break down nucleic acids, membranes, and proteins, which ultimately leads to cell death [100,101]. The antagonism between ROS scavengers and producers regulates the ROS level [102] [Figure 3].

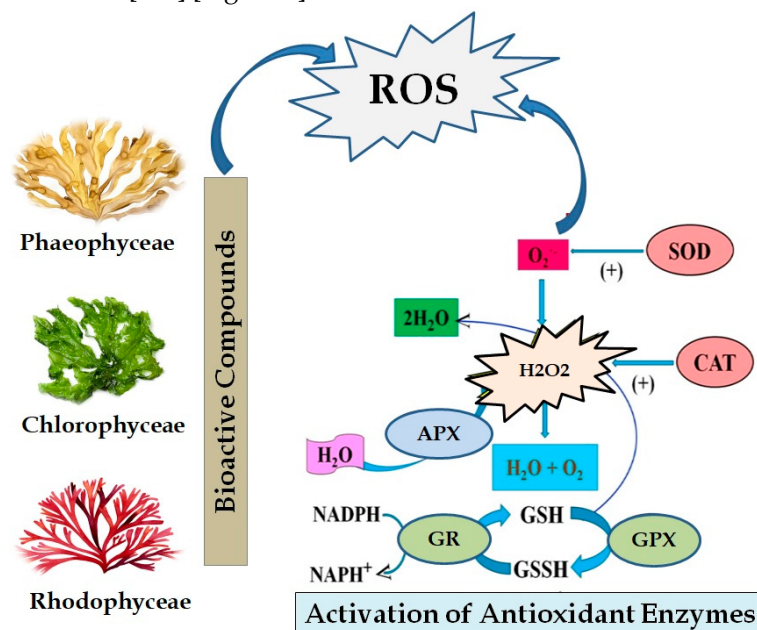


Figure 3. Schematic representation of antioxidant activity of seaweeds by the activation of bioactive enzymes.

Seaweeds have recently received significant attention for their potential as natural antioxidants. Antioxidant activity of marine algae may arise from carotenoids, tocopherols, and polyphenols. Phenolic compounds are nontoxic antioxidants abundantly found in seaweeds. Flavonoids, ascorbic acid, phenols, and glutathione reductase are some of the nonenzymatic antioxidants that are found in higher amounts in macroalgae [103]. In recent times, researchers have focused on marine resources to identify marine bioactive compounds for the development of nutritional foods and novel therapeutic drugs. The phenolic content in seaweed corresponds to an increased antioxidant property. Brown seaweeds, such as *A. nodosum*, *Fucus*, and *Sargassum*, exhibit the highest content of phenols

and phlorotannins. These types exhibit a phenolic content of 12–14%, whereas red and green algae show a significantly lower content of less than 1% [104,105].

4.2. Role of Seaweeds in Alleviating Plant Abiotic Stresses

Droughts, salinity, heat, cold, heavy metals, and nutrient deficiency are the most severe abiotic stresses affecting plant growth, production, and metabolic processes. Extracts from seaweed are reported to improve plant growth and yields against various abiotic stresses. Several studies have shown the positive effect of seaweed extract on plant resistance to abiotic stresses. Putting seaweed extract on the leaves of wheat plants during drought stress improves their growth and yield and the amount of organic solutes they store [106]. According to Mansori et al. [107], the higher amounts of total phenolics and activities of different antioxidant enzymes in common beans help lower drought stress. The application of seaweeds under drought stress significantly increases the vegetative and reproductive parameters of the strawberry plant [108]. Under drought conditions, seaweed extract helps spinach growth by improving the water balance in the leaves, keeping the cell turgor pressure steady and opening up more stomata [109]. In soybean, seaweed extracts enhance drought tolerance, growth, biomass, and activities of antioxidant enzymes by regulating genes that respond to drought stress [110]. As with drought stress, several seaweed extracts are involved in reducing the sodium level and mitigating harmful effects of saline stress in various plants.

Optimum temperature (25–30 °C) is required for plant growth and the entire life cycle. It has been reported that <20 °C or >30 °C affects plant growth, biomass, nutrient uptake, and yields. Bradacova et al. [111] attempted to mitigate cold stress for maize growth, biomass, and nutrient uptake by seaweeds. For example, the application of three different seaweed extracts improved the root length and uptake of macro- and micronutrients under cold stress. The *A. nodosum* seaweed extract alleviates the negative effects of high-temperature/heat stress in brassica and soybean [112,113]. Most researchers have tried to alleviate drought, salinity, and heat stresses by seaweed extracts. However, some researchers have focused on alleviating nutrient deficiency in soil by seaweeds. Two commercial seaweed extracts were used to mitigate iron chlorosis in tomato as well as to increase growth, biomass, activities of antioxidant enzymes, and concentrations of various micronutrients (particularly iron) under iron-deficiency conditions [114]. In another study, the foliar application of seaweed extract increased the relative growth, altered activities of antioxidant enzymes, and reduced the rate of respiration in lettuce under potassium-deficiency conditions [115]. These reports clearly demonstrate that seaweed applications help to mitigate nutrient deficiencies, minimizing the use of inorganic fertilizers. Interestingly, seaweeds have also been reported to remove/reduce the concentrations of heavy metals in plant tissues. A mixture of seaweeds in radish-cultivated soil was shown to reduce the contents of lead, copper, zinc, and nickel in the soil and shoot and root tissues of radish [116]. Similarly, seaweed has been reported to enhance growth and biomass and reduce the over accumulation of copper and copper toxicity in barley [117]. These findings suggest that seaweed mixtures in soil alleviate heavy-metal stress for plants and play an important role in soil heavy metal bioremediators and as plant biofertilizers. However, seaweed management is essential to balance high yields and high quality and environmental and human safety. The molecular mechanisms of plants under abiotic stresses have been extensively studied. However, a detailed study on the specific genes induced by seaweeds under abiotic stresses remains unexplored. There are not many reports that show seaweed effects at the molecular level, however. A recent transcriptome analysis of maize treated with seaweed extracts under drought stress found that 380 upregulated genes were involved in nitrate transportation, signal transmission, photosynthesis, transmem-

brane transport of various ions and glycogen, and starch biosynthetic processes. Further validation of the identified genes by qRT-PCR will help identify specific genes induced by seaweed under drought stress [118]. This type of molecular study should be carried out in the future to understand the real mechanisms of seaweeds under abiotic stresses. Researchers have extensively studied the impact of various seaweed extracts on different abiotic stresses in a variety of plants, as shown in (Table 2).

Table 2. Applications of seaweeds for improving growth, biomass, antioxidant activities, nutrient uptake, and more under various abiotic stresses.

Common Name of the Plant	Botanical Name of the Plant	Various Abiotic Stresses	Seaweeds Used to Mitigate Abiotic Stresses	Effects of Seaweeds Under Abiotic Stress	References
Chickpea	<i>C. arietinum</i>	NaCl (50 and 150 mM)	<i>S. muticum</i> and <i>Jania rubens</i>	Increased shoot dry weight; shoot length; root dry weight; photosynthetic pigments; soluble sugars; phenols; K ⁺ concentration in shoot and root; activities of SOD, POD, CAT and APX. Reduced Na ⁺ level in root and shoot, H ₂ O ₂ , and MDA content.	[119]
Foxtail fern	<i>A. aethiopicus</i>	NaCl (2000 and 4000 ppm)	<i>A. nodosum</i>	Increased branch length, branches per plant, fresh and dry weight per plant, CAT and SOD activities, total chlorophyll content, soluble sugar content, proline content, photosynthetic rate, transpiration rate, and stomatal conductance.	[120]
Tomato	<i>S. lycopersicum</i>	NaCl (6.3 dS m ^{−1})	<i>A. nodosum</i>	Increased root-to-shoot ratio, leaf area, shoot fresh weight, root dry weight, fruits fresh weight, harvest index, firmness, and number of fruits.	[121]
		NaCl (2, 4, 8 dS m ^{−1})	<i>U. lactuca</i>	Increased shoot weight, leaf area, root length, soluble sugars, total proteins, chlorophyll a and b, and total carotenoids. Reduced H ₂ O ₂ concentration in leaves.	[122]
Barley	<i>H. vulgare</i>	NaCl (350 mM)	<i>Cystoseira mediterranea</i>	Increased seed germination, plant height, root length, fresh and dry weight of shoot and root, and chlorophyll contents. Reduced membrane integrity, MDA, and H ₂ O ₂ .	[123]
		Heavy metals (Cu-induced stress)	<i>Fagopyrum esculentum</i>	Increased length and biomass of leaf and root.	[117]
Giant milkweed	<i>C. procera</i>	NaCl (15 dS m ^{−1})	<i>S. angustifolium</i>	Increased plant height; specific leaf area; root length and volume; root and shoot dry weight; K ⁺ uptake; chlorophyll a and b; and activities of CAT, SOD, POD, and ascorbate. Decreased electrolyte leakage and sodium uptake.	[124]
Wheat	<i>T. aestivum</i>	NaCl (50–250 mM)	<i>U. lactuca</i>	Increased seed germination, fresh dry matter, and activities of SOD and CAT.	[125]
		NaCl (150 and 200 mM)	<i>S. dentifolium</i> and <i>P. gymnospora</i>	Increased fresh and dry weight; chlorophyll a and b; and activities of SOD, CAT, POD, and APX in shoots and root. Reduced MDA content in shoot and root.	[126]
		Drought (40% of field capacity)	<i>S. denticulatum</i>	Increased shoot height, fresh and dry weight of shoot, chlorophyll content, starch germination rate, length of shoot and root, total fresh weight, plant total dry weight, plant length, spike length and weight, number of spikelets, seeds yield per plant, seed weight per spike, and 1000 seeds' weight.	[127]
		Drought (40% field capacity)	<i>S. latifolium</i> and <i>U. lactuca</i>	Increased root depth, shoot height, leaf area, chlorophyll a and b, carotenoids, chlorophyll a/b ratio, photosynthetic activity, activities of POD and CAT, and ascorbic acid content.	[106]

Table 2. Cont.

Common Name of the Plant	Botanical Name of the Plant	Various Abiotic Stresses	Seaweeds Used to Mitigate Abiotic Stresses	Effects of Seaweeds Under Abiotic Stress	References
Rice	<i>O. sativa</i>	NaCl (200 mM)	<i>A. nodosum</i>	Increased shoot and root length; fresh and dry weight of shoot and root; concentration of K^+ , Mg^{2+} , and Ca^{2+} ; chlorophyll a and b; total chlorophyll; carotenoid; net photosynthetic rate; transpiration rate; intercellular CO_2 ; stomatal conductance; maximum efficiency of photosystem II; water use efficiency; and activities of SOD and CAT. Reduced sodium, MDA, and H_2O_2 .	[128]
Maize	<i>Z. mays</i>	Cold (12–14 °C)	<i>A. nodosum</i> , <i>Fucus</i> sp., and <i>Laminaria</i> sp.	Increased root length and calcium, phosphorus, magnesium, potassium, zinc, manganese, iron, and copper concentrations in shoot. Reduced necrotic leaf area and leaf chlorosis, subsequently turning into necrotic spots and anthocyanin formation.	[111]
		Drought	<i>K. alvarezii</i>	Increased dry matter of root, leaf, and stem; root volume; number of dry leaves per plant; chlorophyll a and b; chlorophyll index; photosynthetic rate; grain weight, length, and diameter; number of seeds, and total yield. Reduced photo inhibition and lipid peroxidation.	[118]
Radish	<i>R. sativus</i>	Heavy metals (Pb-, Cu-, Zn-, and Ni-induced stress)	<i>U. fasciata</i> and <i>S. lacerifolium</i>	Increased root and shoot length; fresh and dry weight of shoot and root; leaf area; concentrations of nitrogen, phosphorus, potassium, calcium, and magnesium in shoot and root; carbohydrate and protein contents in shoot and root; chlorophyll a and b; and carotenoids. Reduced the contents of cadmium, lead, copper, chromium, and nickel in shoot and root.	[116]
-	<i>C. mucugensis</i>	Heat stress (40, 45, 50, and 55 °C)	<i>Agardhiella subulata</i> and <i>Hypnea pseudomusciformis</i> ,	Improved seed germination.	[129]
Mustard greens	<i>B. juncea</i>	Heat stress (>20 °C)	<i>A. nodosum</i>	Increased plant height, primary and secondary branches per plant, days to maturity, 1000-seed weight, number of siliqua per plant, biological yield, seed yield harvest index, photosynthetic rate, and chlorophyll content. Reduced MDA content and membrane injury.	[113]
Tomato	<i>S. lycopersicum</i>	Drought	<i>A. nodosum</i>	Increased plant fresh and dry weight, chlorophyll content, and relative water content. Reduced MDA contents.	[130]
		Nutrient stress (iron deficiency)	<i>A. nodosum</i> and <i>Durvillea potatorum</i>	Increased dry weight of leaf and root; iron-chelate reductase; activities of SOD, CAT, and MDA contents in leaf and root; concentrations of iron, zinc, manganese, and copper in root and leaf. Reduced chlorosis.	[114]
Sweet orange	<i>C. sinensis</i>	Drought (50% of evapo-transpiration)	<i>A. nodosum</i>	Increased shoot length, leaf and stem dry weight, and total root length.	[131]

Table 2. Cont.

Common Name of the Plant	Botanical Name of the Plant	Various Abiotic Stresses	Seaweeds Used to Mitigate Abiotic Stresses	Effects of Seaweeds Under Abiotic Stress	References
Common Bean	<i>P. vulgaris</i>	Drought	<i>U. rigida</i> and <i>F. spiralis</i>	Increased chlorophyll a and b and glycine betaine content; plant height; dry weight; total phenolic content; and activities of SOD, CAT, and APX.	[107]
		NaCl (50 and 100 Mm)	<i>Gelidiumvavagum</i>	Increased leaf length and width, leaf area, leaf fresh weight, total phenolic compounds, proline, total carbohydrates, free amino acids, chlorophyll a and b, POD, SOD, APX, CAT, and PAL. Reduced electrolyte leakage and MDA contents.	[132]
		Drought	<i>U. rigida</i> and <i>F. spiralis</i>	Increased shoot length, dry weight, chlorophyll a and b, and glycine betaine content in leaves, polyphenol content in leaves, and activities of SOD and APX in leaves. Reduced MDA content in leaves.	[107]
Soybean	<i>G. max</i>	Drought	<i>A. nodosum</i>	Increased relative water content, stomatal conductance, and antioxidant activity. Increased plant height; number of nodules in root; root dry weight; number of pods per plant; CO ₂ assimilation rate; stomatal conductance; transpiration rate; carboxylation efficiency; and activities of SOD, CAT, and APX.	[110]
		Heat stress (40 °C)	<i>A. nodosum</i>	Reduced leaf temperature, reductase nitrate, and proline concentration.	[112]
Faba bean	<i>V. faba</i>	NaCl (150 and 200 mM)	<i>S. dentifolium</i> and <i>P. gymnospora</i>	Increased fresh and dry weight; chlorophyll a and b; and activities of SOD, CAT, POD, and APX in shoots and root. Reduced MDA content in shoot and root.	[126]
Strawberry	<i>F. × ananassa</i>	Drought (50% field capacity)	<i>A. nodosum</i>	Increased number of leaves, length of the longest leaf, leaf area, number of flowers and fruits, chlorophyll content, and fresh and dry weight of root and leaf.	[108]
Spinach	<i>S. oleracea</i>	Drought (50% evapotranspiration)	<i>A. nodosum</i>	Increased leaf relative water content, specific leaf area, and fresh and dry weight of leaf. Reduced ferrous ion-chelating ability.	[109]
Lettuce	<i>L. sativa</i>	Nutrients stress (potassium deficiency)	<i>A. nodosum</i>	Increased leaf number, leaf length, biomass fresh weight, biomass dry matter, root fresh weight, root dry matter, root length, relative growth, activities of SOD and CAT, leaf photosynthetic rate, stomatal conductance, internal CO ₂ concentration, leaf fluorescence, chlorophyll a and b, total chlorophyll and K ⁺ concentration.	[115]
Okra	<i>A. esculentus</i>	Nutrient stress (nitrogen, phosphorus, and potassium deficiency)	<i>E. maxima</i>	Enhanced seedling vigor and increased length of shoot and root length, number of leaf and root, stem thickness, fresh and dry weight of shoot, and root and leaf area.	[133]

5. Conclusions

Recently, seaweeds have become popular as potential green fertilizers or biostimulants to enhance crop cultivation. There are many bioactive compounds, vitamins, carbohydrates, minerals, and phytochemicals in seaweeds. The main ones are gibberellic acids, auxin, and cytokinins, which help plants grow, develop, and produce more. Moreover, seaweeds are the best alternative source for plant biostimulants. Further, it helps to mitigate various abiotic stresses in plants by enhancing ROS activity and thus improving the crop yield. In summary, increasing soil health along with sustainable crop productivity and profitability

under challenging environmental conditions can be significantly influenced by technologies for amending soil with seaweed extract.

Moreover, future research should focus on integrating machine learning approaches to model seaweed–soil–plant interactions, optimize application strategies, and predict long-term outcomes in agricultural systems. These innovations will aid in efficient resource use, improved soil fertility, and broader adoption of eco-friendly practices. In addition, large-scale cultivation of selective seaweed species using high-efficiency, low-cost protocols can further support the development of sustainable biofertilizers. Coupled with zero-waste supply chain management and responsible harvesting practices, this approach not only enhances agricultural productivity but also ensures the protection of marine biodiversity and long-term ecosystem health. Finally, conducting a meta-analytic study in this research area will help in understanding the role of seaweeds in improving abiotic stress tolerance in plants. Therefore, such a review article should be initiated in the future, which will help in improving this research area.

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Abbreviations

The following abbreviations are used in this manuscript:

United Nations	UN
Food and Agriculture Organization	FAO
Compound Annual Growth Rate	CAGR
European Union	EU
Phycobiostimulants	PBSs
Reactive Oxygen Species	ROS
Hydrogen Peroxide	H ₂ O ₂
Superoxide Dismutase	SOD
Ascorbate Peroxidase	APX
Guaiacol Peroxidase	POD
Catalase	CAT
Malondialdehyde	MDA
Cation Exchange Capacity	CEC
Heavy Metal	HM
Biochemical Oxygen Demand	BOD
Dissolved Organic Carbon	DOC
Dissolved Oxygen	DO
Total Suspended Solids	TSSs

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