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Seaweed as Bio-Stimulant for advancing Crop Sustainability: A Review

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Abstract

Seaweeds are an important marine resource that has varied uses in contemporary agriculture. Extracts of different seaweeds have long been used in agriculture to improve plant growth and enhance yield. In the present scenario, excessive use of synthetic chemicals and pesticides leads to a serious global health threat and agricultural land pollution worldwide. Therefore, natural plant growth promoters and fertilizers like seaweeds should be promoted for their encouraging findings. Moreover, this requires seaweed extract-based bio-stimulants, which enhance plant growth and improve the overall resistance of plants. Apart from that, it also enhances the health and fertility of the soil. Thus, the current review is focused on reviewing the various extraction processes of seaweed extract-based bio-stimulant and its function in promoting plant growth, alleviating abiotic and biotic stresses in plants, and improving soil quality by enumerating the mechanisms underlying these processes. The review briefly covers the important agricultural applications of extracts from seaweed and their future prospects.

Keywords:
Bio-stimulants, Essential elements, Micro-biome, Seaweed, Sustainable

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Introduction

The use of synthetic growth promoters and mineral fertilizers has been a common practice agriculture for many years. However, continuous use of inorganic fertilizers in traditional farming is becoming less popular because of its adverse effect in altering the chemistry of the soil, making it less congenial for plant growth (Srijaya *et al.*, 2010). Moreover, the synthetic plant protection products have a serious, harmful impact on human health (Camargo *et al.*, 2006). Also, with the challenges posed by climate change, pesticide resistance, and the diminishing availability of land due to growing populations, the need for inventive agricultural practices has become increasingly urgent. Keeping the views, there has been significant exploration into finding organic agricultural inputs that are not only beneficial for humans but also environmentally sustainable. Therefore, new natural materials that can be used as fertilizing materials or bio-stimulants of plant growth are being developed. One of the most underutilized biological resources is the marine environment, which contains a vast array of organisms with unique biological properties, for example, seaweeds (Ibañez *et al.*, 2012). The application of liquid seaweed fertilizers or bio-stimulants across various crops is intended to replace commercial chemical fertilizers and lower production costs. Liquid fertilizers, extracted from seaweeds, have been shown to outperform chemical fertilizers due to their high levels of organic matter, micro- and macroelements,

Table 1. Commercial Seaweed extract used in Agriculture (Source: Nabti *et al*., 2017)

Product name	Seaweed name	Application
Acadian	*Ascophyllum nodosum*	Plant growth Stimulant
Agri-Gro Ultra	*Nodosum Macrocystis*	Plant growth Stimulant
AgroKelp	*Ascophyllum nodosum*	Plant growth Stimulant
Fartum	*Ecklonia maxima*	Biofertilizer
Kelpak	*Durvillea antarctica*	Plant growth Stimulant
Sea Winner	*Durvillea potatorum*	Plant growth Stimulant
Sagrika	*Kappaphycus alvarezzi*	Plant growth Stimulator

vitamins, fatty acids, and growth regulators (Sathya *et al*., 2010). Agricultural bio-stimulants encompass a wide range of formulations, including compounds, substances, and other products like microorganisms, trace elements, enzymes, plant growth regulators (PGRs), and macroalgal extracts. These are applied to plants or soils to regulate and enhance the crop's physiological processes, thus improving their efficiency (Table 1). As per the European Biostimulant Industry Council (EBIC), "agricultural bio-stimulants act on the physiology of the plant through different pathways to improve crop vigor, yields, quality, and post-harvest shelf life/conservation (EBIC, 2012).

Bio-stimulants are derived from biological sources or microorganisms and are administered to plants via root drench, foliar spray, or a combination of methods. Their purpose is to amplify the inherent processes responsible for optimal plant nutrient utilization and growth while boosting resistance to both abiotic and biotic stressors, irrespective of the nutrient composition (Ali *et al*., 2021; Khan *et al*., 2009; Mukherjee *et al*., 2020). Algal extracts, classified as bio-stimulants rather than fertilizers, induce defense and growth responses without containing fertilizer compounds. Recent focus on seaweed-based extracts reveals diverse bio-stimulatory compounds, such as carbohydrates, amino acids, phytohormones, osmo-protectants, and proteins (Bhaskar *et al*., 2005; Michalak *et al*., 2015). Seaweed-based bio-stimulants not only improve stress tolerance, nutrient uptake, growth, and yield but also reduce seed dormancy and enhance root systems, flowering, fruit quality, taste, and overall produce quality, leading to enhanced crop productivity.

Seaweeds, as macroalgae, are integral to marine and coastal ecosystems, representing most of its biomass, which is about 2,5000-30,000 species (Shayen *et al*., 2022), contributing to rich biodiversity. Commercially utilized in agriculture, three classes of seaweeds (brown, red and green) are available, with some being widely distributed and others region-specific (Table 2). The recent influx of *Sargassum* in the Americas and the Caribbean, while causing environmental challenges, presents an opportunity for innovative valorization of the biomass (Oxenford *et al*., 2021).

Table 2. Important Seaweed species (Source: Ali *et al*., 2021)

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

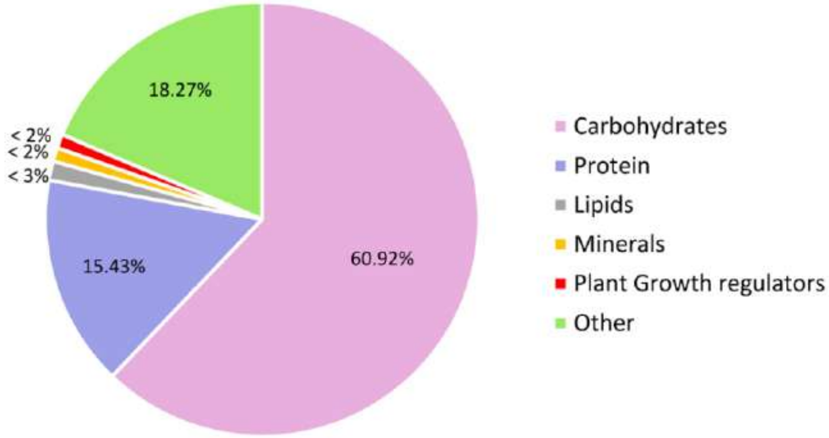

Fig.1. Composition of Seaweed extracts (Source: Ali *et al.*, 2021)

This can be accomplished by developing bio-stimulants and other bioproducts derived from seaweed. Seaweed extracts consistently contribute to promoting plant growth (Khan *et al.*, 2009), increasing yields, and enhancing tolerance to abiotic and biotic stresses, presenting a promising and sustainable approach for farmers. Integration into farming systems, including integrated crop management, allows for the reduction of chemical pesticide usage by substituting synthetic inputs with seaweed extracts or products (Mukherjee *et al.*, 2020). The manner in which seaweed extracts are applied plays a significant role in eliciting plant responses, with commonly used methods encompassing foliar application, root application, or a combination of both. The application to soil or growing medium through fertigation, drenching, or dripping is also viable. However, foliar sprays at concentrations equal to or less than 0.05% v/v have been identified as optimal for crops, resulting in effective disease control and increased yields. Foliar applications are favored for their immediate interaction with plant tissues, as foliar absorption occurs nearly instantly (Kumar *et al.*, 2021; Mukherjee *et al.*, 2020). The adsorption of extracts by soil particles is a common occurrence, potentially diminishing immediate mobility. The recommended application intervals for these extracts have been identified as approximately every 10–14 days to achieve optimal plant responses (Ali *et al.*, 2021). Ongoing efforts aim to comprehend the comprehensive mechanisms of seaweed extracts in influencing overall crop productivity through a global exploration of differential gene expression. The review specifically focused into the impacts of seaweed extracts on economically significant crops, aligning with their mechanisms of action at the genetic and metabolic levels. It underlines the utilization of these extracts in conjunction with minimal chemical inputs for the most sustainable agricultural outcomes, both economically and environmentally.

Bioactive and Elicitor Constituents of Seaweed Extracts

Seaweed extracts comprise a diverse range of bioactive compounds such as such as carotenoids, proteins, dietary fiber, vitamins, minerals, omega-3 fatty acids and polysaccharides (Michalak *et al.*, 2015) that trigger and directly stimulate both plant growth and defense responses (Mukherjee *et al.*, 2020). Participating in various metabolic pathways, these compounds include polysaccharides, plant growth-promoting hormones, fatty acids, sterols, carotenoids, oxylipins, minerals, peptides, amino acids and proteins, lipids, polyphenolics, and phlorotannins (Fig. 1)—all possessing biological activity (Khan *et al.*, 2009; Kumar *et al.*, 2021; Salehi *et al.*, 2019). The composition of these substances within the extracts varies depending on the class and species of seaweed, as well as the extraction method employed. Seaweeds typically contain polysaccharides constituting up to 76% of dry weight, with content showing seasonal fluctuations (Kumar *et al.*, 2021). Galactans, fucoidan, laminarin, and alginates are among the most crucial algal polysaccharides, and these are proportionally present in seaweed extracts. Extraction methods significantly impact the composition of seaweed extracts, converting complex molecules, including polysaccharides, into highly bioactive oligomers, while potentially degrading small molecules like hormones (Jonsson *et al.*, 2020; Kumar *et al.*, 2021). Seaweed extracts boast various carotenoids, potent antioxidants that contribute to their overall composition. Phenolic compounds, encompassing phenolic acids, flavonoids, isoflavones, cinnamic acid, benzoic acid, quercetin, and lignans, are also found in these extracts. Algal extracts are rich in minerals due to the bioaccumulation of seawater minerals by seaweeds. Furthermore, seaweed extracts contain phytohormones such as cytokinins, gibberellins, auxins, abscisic acid, and betaines (Kavitha *et al.*,2009; Michalak *et al.*, 2015). The impact of these substances on crops is contingent on factors like the plant type, its receptor mechanism, and the application method, be it foliar, root feeding, or a combination of both.

Fig.2. Phaeophyceae (Brown), Rhodophyceae (Red) and Chlorophyceae (Green) Seaweed extracts

Preparation and application techniques of seaweed extracts for plants

Liquid extracts derived from various seaweeds are increasingly being recognized for their importance as foliar sprays or soil conditioners for a range of significant crops, including grasses, cereals, flowers, and vegetable species (Gireesh *et al*., 2011; Dhargalkar *et al*., 2005; Michalak *et al*., 2015; Rathore *et al*., 2009). The selection of the extraction method must address the intricate composition of seaweed and ensure the preservation of biologically active molecules with bio-stimulant properties. There are mainly three different techniques are employed: biological method (i.e., enzymatic degradation method), chemical hydrolysis method (i.e., organic, inorganic solvents), and physical extraction method (*i.e*., high pressure and cold process, supercritical fluid extraction) to extract bioactive compounds from seaweeds (Lianfeng Biology www.lianfengbio. com.cn/e-seaweed-extract-fertilizer.htm). The biological method involves utilizing various enzymes produced by microorganisms during their metabolic processes, with seaweeds serving as the nutrient source. In this process, the macromolecules in seaweeds are broken down into micromolecules and water-soluble compounds. This method operates under mild conditions (such as pH and temperature) to maximize the retention of bioactive and nutritious substances within the seaweed. Digestive enzymes like carbohydrases and proteases are used to degrade seaweed tissues, aiding in the release of a range of

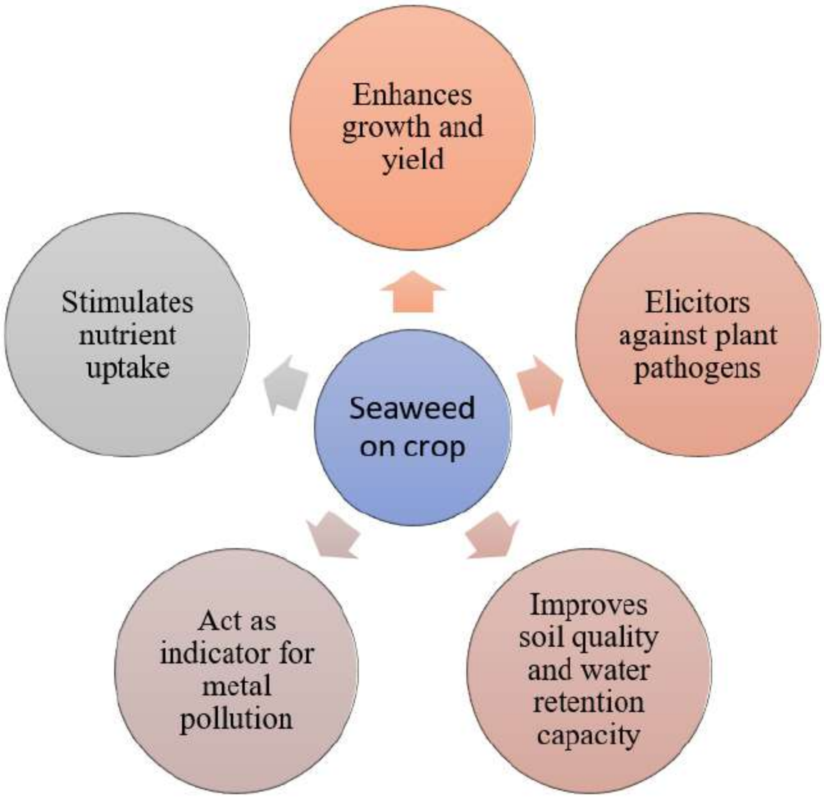

Fig. 3 An illustration of different application of seaweed extract on crops

bioactive compounds, such as antioxidants and total phenolics, from the seaweed (Heo *et al.*, 2003a; Hoe *et al.*, 2003b). In chemical methods, organic and inorganic solvents are used. Organic solvents like methanol (sugar, protein), acetone (carotenoids), chloroform, dichloromethane (lipids, fatty acids), etc are used for extraction while inorganic solvents- mineral acids and distilled water are used (Cho *et al.*, 2007; Kumar *et al.*, 2009; Chinnadurai *et al.*, 2013). Acid hydrolysis with sulphuric acid to hydrolyze polysaccharides from seaweed like *Laminaria japonica* and *Gelidium amansii* and alkaline extraction with potassium chromate at high pressure to breakdown the polysaccharide chain to smaller units is the most widely adopted method. The second solvent that is used for the production of algal extracts is distilled water to extract water-soluble fractions (Shekhar sharma *et al.*, 2013). This method provides a substantial extract yield and a controlled breakdown of polysaccharides into oligomers, which are vital biologically active constituents in seaweed extracts. Mechanical processes like use of blender (Sunarpi Jupri *et al.*, 2010), boiling of seaweed in water (Michalak *et al.*, 2015) and autoclaving of algal biomass with distilled water (Michalak *et al.*, 2015; Sathya *et al.*, 2010) are usually employed.

Effects of Seaweed Extracts on Crops

Over the years, extensive exploration has taken place regarding the potential use of seaweed extracts in crop production to enhance biomass yield and produce quality (Fig. 3). These extracts exhibit positive effects on seed germination, plant growth throughout all stages, and post-harvest (Khan *et al.*, 2009). They have been observed to enhance seedling vigor by increasing root size and density, protecting seedlings from transplantation shock in crops like tomato, cabbage, and marigold. The extracts contain small levels of phytohormones, such as auxins, contributing to improved rooting architecture. Vegetatively propagated plants, like floricultural cuttings, treated with seaweed extracts show increased root density. Furthermore, the extracts enhance water uptake and nutrient absorption, promoting overall vigor and plant growth. Applications of seaweed extracts in maize, cottonwood, and mustard result in improved nutrient uptake, including essential elements like Zn, Fe, B, Cu, Mo, S, Mg, Ca, Mn, and potassium (Shayen *et al.*,

Table 3. Seaweed species, their classification, functions in crop production

Seaweed Species	Classification	Function in Crop	References
Ascophyllum nodosum	Phaeophyceae	Improves plant growth, enhances stress resistance	De Saeger et al. (2020)
Fucus vesiculosus	Phaeophyceae	Soil conditioning, boosts nutrient availability	Yurkevich *et al.* (2022)
Ecklonia maxima	Phaeophyceae	Enhances root development, increases yield	Rengasamy *et al.* (2015)
Ulva Lactuca	Chlorophyceae	Provides organic matter, improves soil fertility	Park *et al.* (2023)
Porphyra yezoensis	Rhodophyceae	Acts as a biostimulant, enhances plant immunity	Kim *et al.* (2024)
Gracilaria vermiculophylla	Rhodophyceae	Improves soil structure, increases microbial activity	Nguyen *et al.* (2023)
Laminaria digitata	Phaeophyceae	Enhances soil moisture retention, provides micronutrients	Bullen *et al.* (2024)
Sargassum fusiforme	Sargassaceae	Boosts plant growth, improves stress tolerance	Wang *et al.* (2023)
Chondrus crispus	Rhodophyceae	Enhances soil fertility, acts as a natural growth enhancer	Alkhalaf, *et al.* (2021)
Gelidium amansii	Rhodophyceae	Provides essential nutrients, improves soil texture	Li *et al.* (2019)
Laminaria japonica	Phaeophyceae	Enhances nutrient uptake, promotes root growth	Li *et al.* (2022)
Sargassum polyschides	Sargassaceae	Increases plant yield, improves stress resistance	Thompson *et al.* (2020)
Padina pavonica	Phaeophyceae	Improves soil health, enhances microbial activity	Chbani *et al.* (2019)
Alaria esculenta	Phaeophyceae	Enhances growth rates, improves soil structure	Stevant *et al.* (2017)
Eisenia bicyclis	Phaeophyceae	Increases nutrient availability, supports plant growth	Avila-Peltroche *et al.* (2024)

2022). Seaweed extracts also exhibit phytohormonal activity, influencing endogenous cytokinins and chlorophyll content in plants. They prevent chlorophyll degradation, leading to increased photosynthetic activity. Additionally, seaweed extracts enhance electron transfer rates, induce early flowering, and increase fruit set, ultimately improving yields in crops like tomato, pepper, and snap bean. Beyond increasing harvestable crop yield, seaweed extracts enhance nutrient quality in crops such as tomato, pepper, lettuce, spinach, cucumber, and strawberry. They lead to increased levels of phenols, antioxidant capacity, vitamin C, anthocyanins, and total phenolic contents. Strawberry plants treated with seaweed extract show improved edible quality, with increased total soluble solids, sucrose, fructose, and the health-promoting compound quercetin. Postharvest applications of seaweed extract also demonstrate positive effects, reducing browning in apples and inhibiting enzymes linked to browning, thus extending shelf life. These benefits are observed irrespective of the application method, whether foliar, soil root drench, or a combination (Mukherjee *et al*., 2020). The organic fraction of seaweed extracts plays a crucial role in eliciting positive growth responses in plants, and their mineral content, while minimal, contributes to stimulating various plant processes for enhanced growth and productivity (Table 3).

Impact of Seaweed Extracts on Plants' Resistance to Biotic Stresses

The dynamic climate shifts and excessive reliance on chemical pesticides have led to the emergence of infectious and resistant pests and pathogens in major crops, resulting in substantial reductions in agricultural yields e (Anderson *et al*., 2004). Seaweed extracts and their bioactive compounds are effectively employed as defence priming agents in plants, stimulating an immune response s (Craigie, 2010; Islam *et al*. 2020). Many seaweed extracts have been reported to exhibits antagonistic activity both *in-vitro* and in field conditions (Table 4). Seaweed extracts also efficiently mitigate infestations caused by borers, aphids, and thrips in sugarcane, preventing substantial economic losses. The decrease in infestation can be attributed to antifeedant effects, growth inhibition, and cytotoxicity on ovarian tissue cells of pests. For example, an acyclic diterpenoid isolated from *Sargassum* demonstrates growth-repellent effects against pink bollworm. Seaweed extracts act as elicitors for plant defense responses against harmful bacteria, fungi, and even viruses, safeguarding crops from significant economic damage. Various extracts from brown, red, and green macroalgae exhibit eliciting effects against harmful bacterial and fungal pathogens. The application of seaweed extracts controls several fungal and bacterial diseases, leading to a reduction in infection levels (Agarwal *et al*., 2021). Beyond eliciting defense against bacterial and fungal pathogens, seaweed extracts have showcased the capability to manage severe symptoms caused by viroids and plant viruses.

Impact of Seaweed Extracts on Plants' Resilience to Abiotic Stresses

Diverse environmental stresses, including drought, high temperature, heavy metals, salt, and freezing conditions, can impede crop productivity. It is projected that by 2050, around 50% of arable lands will face issues related to high salt and drought conditions (Hossain *et al*., 2020). These abiotic stresses often result in the accumulation of reactive oxygen species (ROS), causing harm to the plant system (Raja *et al*., 2023). Notably, plants subjected to seaweed extracts, such as *A. nodosum* and *Sargassum spp*., displayed

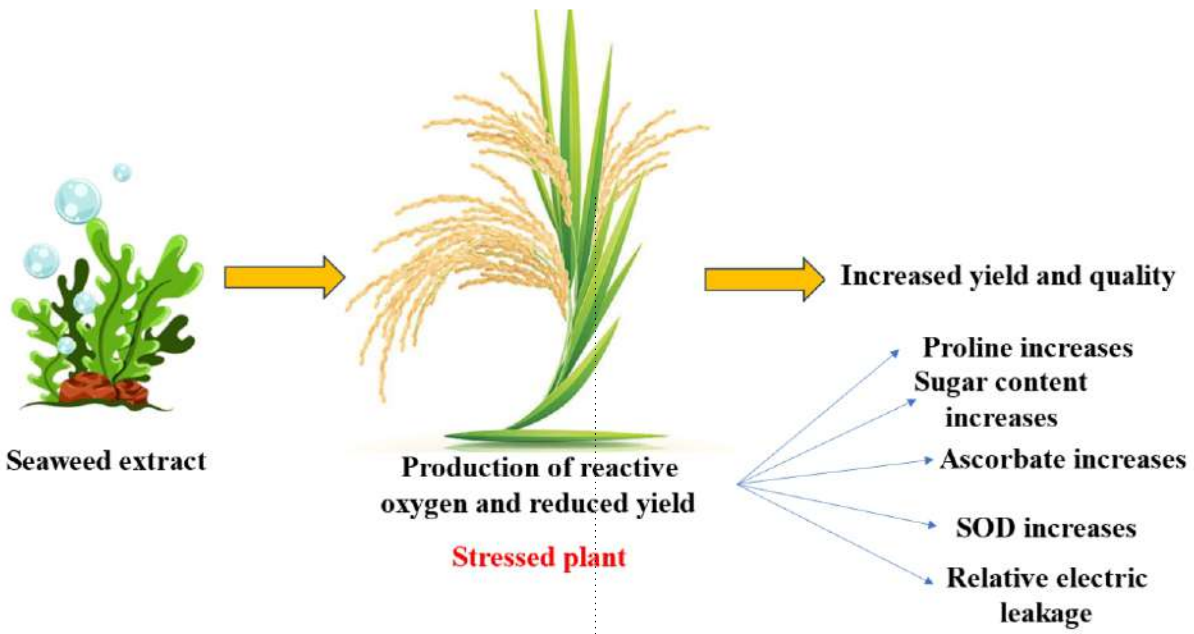

Fig.4. Beneficial effect of Seaweed extracts under abiotic stress

Table 4. Effect of different seaweed extract on biotic resistance in plant

Seaweed species	Diseases	Pathogens	Crop	Response of crop	References
Kappaphycus sp.	Blast	*Magnaporthe oryzae*	Rice	Enhance defense genes and enzymes	Sahana *et al.* (2021)
S. vulgare	Pythium leak	*Pythium aphanidermatum*	Potato	Reduce rotting	Ammar *et al.* (2017)
S. tenerrimum	Cotton Red	*Dysdercus cingulatus*	Cotton	Reduced the nymphal development	Sahayaraj and Mary Jeeva, (2012)
E. maxima	Root knot	*M. chitwoodi* and *M. hapla*	*Arabidopsis thaliana*, sunflower, and tomato	Reduce infection	Ngala *et al.* (2016)
S. fusiforme	Powdery mildew	*Phytopthtora infestans*	Tomato	Reduce infection by 37%	Sbaihat *et al.* (2015)
K.alvarezii sap	Charcoal rot	*Macrophomina phaseolina*	Tomato	Increase defense responsive genes and phytohormones	Agarwal *et al.* (2015)
Sargassum wightii and *Padina pavonica*	Red cotton stainer, greenfly aphid, leaf minor	*Dysdercus cingulatus, Aphis gossypii, Liriomyza trifolii*	Cotton	Insecticidal activity	Asaraja *et al.* (2013)
Caulerpa sertularioides, Laurencia johnstonii, and Sargassum horridum	Citrus greening	*Diaphorina citri*	Citrus	Reduces infection	González-Castro *et al.* (2019)

resilience against the adverse effects of these abiotic stresses. For example, grapevines and tomato plants treated with seaweed extracts demonstrated a substantial reduction in leaf osmotic potential, averting extensive damage. Treating various wheat varieties with *Kappaphycus alvarezzi* extract under salinity and drought stress yielded plants with increased root length, enhanced chlorophyll content, carotenoids, and tissue water content (Patel *et al.*, 2018). The extract also resulted in a significant decrease in electrolyte leakage and lipid peroxidation, a reduction in Na+/K+ ratio, and an elevation in Ca content, effectively mitigating ionic imbalance. Treated wheat plants amassed osmo-protectants, such as proline, amino acids, and total protein. Seaweed extracts also improved freezing tolerance in barley and *A. thaliana*, heightening winter hardiness when exposed to seaweed extract sprays (Sangha *et al.*, 2014). The alleviation of the adverse impacts of drought, cold, and salinity stress via seaweed extracts is facilitated by improved root morphology, the accumulation of non-structural carbohydrates for enhanced energy storage, heightened metabolism, water adjustments, and the increase of proline (Fig. 4). Prominent results prove that seaweed can mitigate abiotic stress in plants (Table 5).

Impact of Seaweed Extracts on Plant and Soil Microbiome Dynamics

Plant surfaces, including both roots and leaves, constitute the rhizosphere and phyllosphere, where dynamic interactions between plants and microbes play a crucial role in influencing plant growth (Bell *et al.*, 2022; Ugarelli *et al.*, 2017). Microbial interactions on external as well as internal surfaces profoundly affect plant growth and productivity. The roots, leaves, and internal surfaces of plants release water-soluble compounds such as amino acids, sugars, and organic acids, influencing the growth of various microorganisms (Ali *et al.*, 2021). The application of bio-stimulants, fungicides, and other inputs on foliage

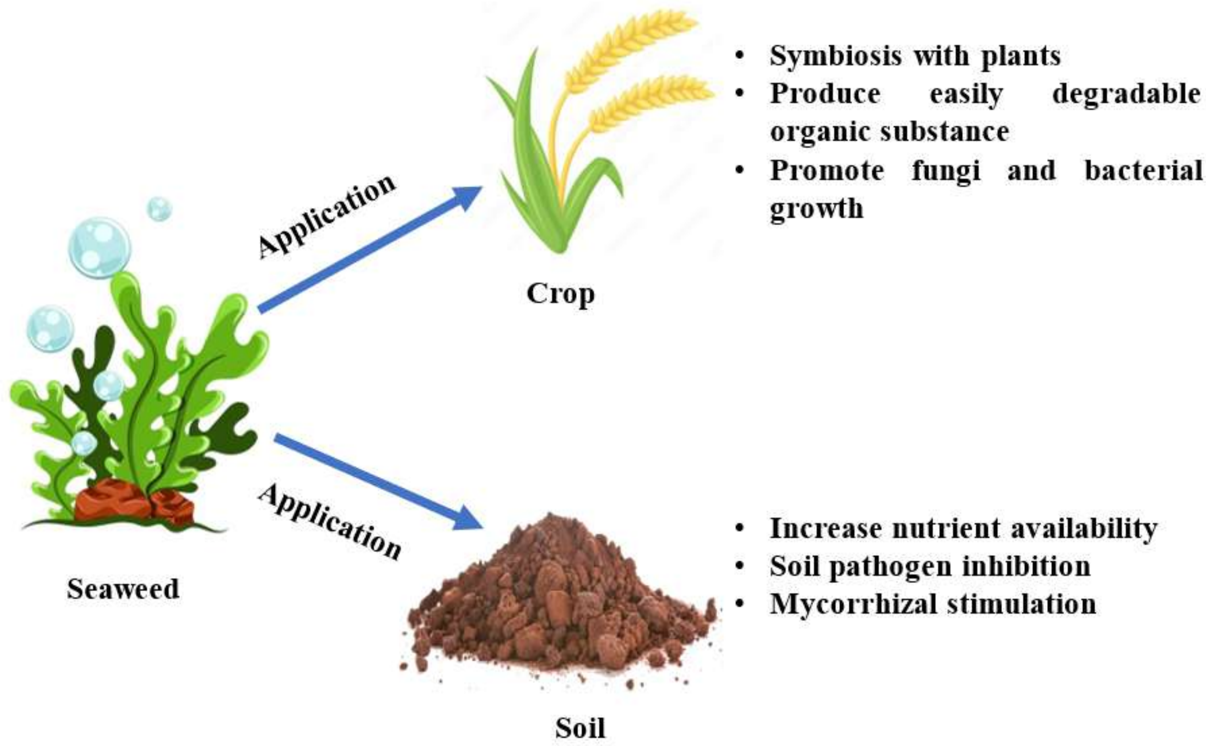

Fig. 5. Rhizospheric and Phyllospheric benefits of the application of Seaweed extract

or soil significantly alters the exudate composition of plant surfaces. Elevated levels of exudates in the rhizosphere activate a diverse range of microorganisms, and the composition of root exudates shapes the population structure, size, and activity of these microorganisms (Bell *et al.*, 2022). Not surprisingly, applying seaweed extracts to soil and foliage induces significant effects on the patterns of rhizosphere and phyllosphere microbiomes (Colla *et al.*, 2017). The flourishing and productive growth of plants subjected to seaweed extracts is thought to be influenced by the microbiome effect conditioned by these extracts, potentially amplifying Plant Growth Promotion (PGP) traits of rhizospheric microbes. A greenhouse investigation on tomato and pepper plants employing *Ascophyllum nodosum* extract (ANE) showcased its influence on bacterial and fungal communities in rhizospheric soils (Renaut *et al.*, 2019). Amplicon sequencing targeting fungal ITS and bacterial 16S rRNA genes unveiled noteworthy differences in species composition (b-diversity) between the ANE treatment and the control, predominantly favoring beneficial microbial groups in the rhizosphere. Likewise, maize plants treated with *Ascophyllum nodosum*-fermented seaweed fertilizer displayed notable impacts on the rhizosphere microbiome, modifying the relative abundance of dominant phyla and influencing bacterial diversity (Chen *et al.*, 2020). Enzymatic activities in the soil, including dehydrogenase, nitrite reductase, urease, and cellulase, exhibited a significant increase after ANE application to the maize rhizosphere (Renaut *et al.*, 2019). In another instance, the application of a seaweed extract bio-stimulant to *Malus hupehensis* seedlings' replant soil elevated the soil activity of invertase, urease, proteinase, and phosphatase enzymes compared to the control (El Boukhari *et al.*, 2020). T-RFLP (Terminal restriction fragment-length polymorphism) analysis indicated notable alterations in the soil fungal community following seaweed extract application (Wang *et al.*, 2016). When analyzing the microbial metabolic activity of strawberry plants' rhizosphere soil under greenhouse and field conditions, *Ascophyllum nodosum* extract treatment demonstrated significant increases in functional diversity, colony counts, and soil respiration (Ali *et al.*, 2021). Despite these vital discoveries, the fundamental microbiome effects and interactions between plants and microbes remain insufficiently investigated. There is an increasing necessity to utilize metagenomic tools to completely unravel the magnitude of microbial community variations triggered by seaweed extract application. Such outcomes would advance our understanding of plant-microbe interactions in seaweed extract treatments, contributing to the informed utilization of these extracts in sustainable agricultural production (Fig. 5).

Mode and Mechanisms of Bio-stimulatory Activities

Seaweed extracts confer numerous growth benefits when applied to plants. However, these advantages primarily stem from their stimulatory properties, triggering a cascade of reactions within the plant that leads to overall growth and enhanced resistance to both biotic and abiotic stress. It's important to note that, given the myriads of bioactive ingredients in seaweed extracts, no single component can be solely credited for the observed positive effects. Fraction trials have revealed that no isolated fraction can reproduce all the effects observed with the original

Table 5. Effect of different seaweed species on abiotic stress in plant

Seaweed species	Abiotic stress	Plant	Response	References
K. alvarezii	Water stress	Maize	Increase cob length, no. of grains/cob, filled grains	Trivedi *et al*. (2018)
S. muticum, Jania rubens	Salt stress	Chickpea	Increases pigments and SOD	Abdel Latef *et al*. (2017)
Fucus spiralis	Salt stress	Wheat	Enhanced seed germination, growth and antioxidant enzymes	Chernane *et al*. (2015)
Kelpak®	Drought stress	Cowpea	Increase in photosynthetic pigments, shoot and nodule production	Voko *et al*. (2022)
K. alvarezii	Salt stress	Tobacco	Increase photosynthesis	Kumari *et al*. (2022)
K. alvarezii	Drought stress	Maize	Enhancement of root growth, seed development and antioxidant enzymes	Kumar *et al*. (2020)
Dictyota dichotoma	Salt stress	Rice	Enhancement of seed germination	El-Katony *et al*. (2021)

whole extract, emphasizing the synergistic interaction of components for an overall positive response in the plant system. Each component may act independently or interactively on various metabolic networks. Plants treated with seaweed extracts exhibit enhanced capabilities for nutrient acquisition and increased growth and vigor. For example, rapeseed plants treated with *A. nodosum* extract demonstrated heightened nitrogen and sulfur acquisition, correlated with the overexpression of genes encoding root transporters associated with nitrogen, iron, and sulfur uptake (Ali *et al*., 2021). Transcript studies in spinach employing *A. nodosum* demonstrated elevated biomass, protein content, chlorophyll, carotenoid content, flavonoids, phenolics, and antioxidant activity (Fan *et al*., 2013). Comparable investigations in rapeseed and tomato exhibited differential gene expression linked to carbon, sulfur, and nitrogen metabolism, photosynthesis, and diverse metabolic pathways, collectively contributing to enhanced growth (Ma *et al*., 2017). Treatment with *A. nodosum* extracts protected plants from induced cold stress, upregulating key genes for cold stress tolerance. Similarly, seaweed extract-treated plants exhibited significant tolerance to freezing stress, with upregulated genes associated with freezing tolerance (De Saeger *et al*., 2020). Under drought conditions, seaweed extract-treated plants maintained higher relative water content, improved water use efficiency, and reduced oxidative damage. The extracts also played a role in mitigating salinity stress, upregulating genes linked to abiotic stress tolerance and reducing sodium levels in plants. In addition to abiotic stresses, seaweed extracts activate defense mechanisms against biotic stressors. The polysaccharides in seaweed cell walls and their derived oligosaccharides trigger an oxidative burst and activate diverse defense pathways, resulting in the buildup of pathogenesis-related proteins, defense enzymes, and phenolic compounds. Seaweed extracts from *Ulva spp*. and other brown seaweeds demonstrated increased activity of defense enzymes in barrel clover under pathogenic infection, showcasing a plant-based defense mechanism (Ali *et al*., 2021). Extracts from brown seaweeds (e.g., *Sargassum* and *Ascophyllum*) upregulated JA and ET pathways, while a red seaweed extract (*Acanthophora spicifera*) induced both SA and JA pathways, highlighting a harmonized modulation of defense pathways (Shukla *et al*., 2021). Seaweed extracts, with their diverse bioactive molecules, present a holistic approach to plant growth and defense, eliciting complex metabolic responses that optimize protection against both biotic and abiotic stresses. The observed effects do not stem from a singular defense pathway or a specific set of genes but originate from the intricate interplay of multiple genes in a coordinated and harmonious manner.

Utilizing Seaweed Extract in Integrated Crop Management: A Shift towards Sustainable Agriculture Paradigm

With global agriculture intensifying, there is a heavy reliance on synthetic chemical inputs, but these come with drawbacks, especially when overused. While optimal usage can lead to higher returns, it can also result in toxic and lasting negative effects on the environment and human health, particularly through improper and excessive application. Overuse may lead to pesticide resistance, environmental issues like eutrophication and water contamination, and residual harm to humans and animals, along with increased production costs. Additionally, non-target effects can cause the decline of beneficial organisms, impacting the overall food chain and biodiversity. The World Health Organization reports millions of cases of acute occupational pesticide poisoning in developing countries, leading to increased regulations in developed countries due to environmental persistence and toxic effects on humans. To address these concerns, countries are implementing laws and management programs, emphasizing integrated approaches that minimize synthetic chemical use and promote natural systems and organic inputs. This era sees the adoption of holistic methods, including integrated crop management, nutrient management, disease management, and pest management. Seaweed extract bio-stimulants/products emerge as ecologically safe alternatives, highlighted in previously for their positive impact on crop returns. The integrated management approach seeks to control disease outbreaks using multiple methods, making seaweed extracts an attractive component due to their non-toxic nature and various beneficial roles. Feasibility studies indicate farmers' willingness to use seaweed extracts as green alternatives, showing higher returns when used with reduced chemical inputs. Studies in the tropics reveal lower disease levels and higher yields when seaweed extracts are used in conjunction with safe fungicides. A five-year research study in the Caribbean region demonstrates significant disease reductions, improved marketable yields, and reduced pest and disease incidence through the integration of seaweed extracts in tomato, pumpkin, pepper, and cowpea cultivation (Ali *et al*., 2021). These findings highlight the important role of seaweed extract sprays as organic components for widespread crop use. Increasing seaweed extract and organic input use allows a two-thirds reduction in chemical application rates without negatively impacting yields. Seaweed-based products, classified as bio-stimulants, organic nutrients, or plant boosters, find extensive use in crops certified for organic and environmentally-friendly production or under integrated crop management systems.

Future Remarks

Summarizing the above findings, the aforementioned discoveries make it clear that seaweed extracts not only promote plant growth but also trigger plant defense mechanisms against both biotic and abiotic stresses. Operating as bio-stimulators, seaweeds elevate plant nutrient value without detrimental effects on plant health or seed germination, fostering the development of roots and root hairs. This can be ascribed to their abundant content of plant growth-regulating phytohormones such as IAA, gibberellins, and cytokinins. Cytokinin induction enhances plant resistance to diseases, and certain brown seaweeds containing water-soluble polysaccharides act as inducers of systemic plant resistance. Seaweed extracts activate enzymes catalyzing lignin and phenolic synthesis against pathogen attacks, and JA/SA signaling plays an important role in induced systemic resistance (ISR) against various pathogens. This signaling is also linked to the trans-generational effect of resistance. Seaweed extracts induce diverse biochemical pathways, increasing flavonoid production, aiding in microorganism colonization, including plant growth-promoting rhizobacteria (PGPR). Rich in micro- and macronutrients like N, P, K, Ca, S, Mg, Zn, Mn, and Fe, seaweeds improve plant nutrient status. Reports suggest seaweed extract use for sustainable agriculture, altering soil nutrient indices and fertility, leading to significant crop production increases. Seaweed extracts can be applied as seed treatments in powder or liquid form, and green nanoparticle synthesis from seaweed extracts has been reported. They can be used with or instead of chemical fertilizers, reducing chemical soil applications—an important aspect of sustainable agriculture, particularly relevant in developing countries aiming to minimize harmful chemical usage for agricultural purposes.

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