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From sea to soil: Exploring the multifaceted role of seaweeds in sustainable agriculture for disease management and crop health enhancement

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Abstract

In recent times seaweed-based products have emerged as a promising tool in sustainable agriculture, offering a multifaceted approach for managing plant diseases. This review explores the mechanisms by which seaweeds manage plant diseases. Seaweed extracts are rich in bioactive compounds and exhibit remarkable antifungal and antibacterial properties. Hence, it is a potential biocontrol agent against plant pathogens. Seaweed extracts stimulate plant defense mechanisms, enhancing innate immunity and increasing disease resistance. Moreover, applying these extracts to soil helps to faster beneficial microbial populations in the rhizosphere. Several studies have reported the efficacy of seaweeds in managing the wide spectrum of plant pathogens and crop growth parameters. Hence, resolving these challenges will be a promising path towards sustainable and eco-friendly disease management. Hence, this review brings to light how seaweeds can revolutionize disease management strategies.

1. Introduction

Seaweeds referred to as "marine macro-algae" belong to the kingdom Chromista, which is classified into three groups, *viz.,* red algae, green algae and brown algae. The seaweeds may be single cells (microalgae) or multicellular (gigantic seaweeds) (Raj *et al*., 2020). Over 10,000 species of macroalgae have been recorded which contribute approximately 10 per cent of the total marine production worldwide (Agarwal *et al*., 2021). The beneficial role of seaweeds has been recognized in several fields of agriculture. These macroalgae possess numerous strategies for acquiring photosynthetically active carbon, which plays a crucial role in maintaining the quality of the environment (Agarwal *et al*., 2021). Jolivet *et al*. (1991) reported seaweed extracts can mitigate plant diseases, improve plant growth and increase yield. Numerous variety of bioactive compounds are abundant in seaweeds (Vijayalakshmi *et al.,* 2022) with antibacterial and therapeutic applications (Arunkumar *et al*., 2005; Raj *et al*., 2016). Seaweed extracts are widely accepted as 'plant biostimulants'.

Seaweed extracts contain bioactive compounds like phlorotannin, polysaccharides, peptides and fatty acids that exhibit antimicrobial activity. These compounds can inhibit the growth of various pathogens such as fungi, bacteria and viruses. Seaweeds have been found to promote the growth and development of fruits and vegetables (Washinton *et al*., 1999). Kannan *et al*. (2019) reported that seaweeds contain growth promoters like auxins, gibberellins and precursors to ethylene and betaine. Throughout the world, an enormous number of chemical pesticides are employed for crop protection. Crop yields are raised by using chemical fungicides to suppress plant pathogenic fungi and market quality continues to improve. However, the usage of fungicides has increased rapidly, which has caused an increase in resistant disease strains and an excess of fungicide residues in the food chain (Pol *et al*., 2023). This has led to a rise in interest in exploring more sustainable, alternative ways to increase the production of crops, human well-being and agricultural productivity (Kaur *et al*., 2023; Santhosha *et al.,* 2023). Thus, exploring the significance of seaweed in agriculture is the need of the day (Kannan, 2019). The uses of algae in different industries and sectors are shown in (Figure 1).

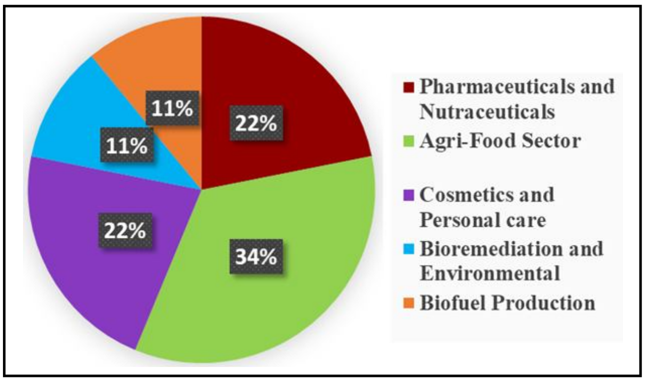

Figure 1: Commercial uses of algae at the world level (Adapted from FAO, 2017).

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2. Types of marine algae

Marine seaweeds are classified into three families Chlorophycaeae (green), Rodophycaeae (red) and Phaeophycaeae (brown) (Raj *et al.,* 2018). The coastal regions of India consist of 844 species of red seaweeds, 216 species of green seaweeds and 194 species of brown seaweeds. Similar to higher plants, green algae also possess chlorophyll, red algae contain phycoerythrin pigment and brown algae contain xanthophylls and fucoxanthin pigments (Abad *et al.*, 2011). Due to their strong biostimulant activity (red algae) *Corralina mediterranea, Jania rubens, Pterocladia pinata* (green algae) *Cladophora dalmatic, Enteromorpha intestinalis, Ulva lactuca* and (brown algae) *Ascophyllum nodosum, Ecklonia maxima, Sargassum* sp. are most frequently used in agriculture (Chatzissavvidis and Therios, 2014). Different seaweed species are shown in (Figure 2).

Figure 2: Various species of seaweeds in plant disease management.

2.1 Brown algae in plant disease management

With over 2,000 species, brown seaweeds are the most abundant group of seaweeds which are mostly found in the rocky coastlines of temperate zones, where their biomass reaches its peak (Khan *et al.*, 2009). Phaeophyta or brown algae, are known for their efficacy in combating plant diseases. Brown algae provide iodine and potash whereas, red seaweed is the source of bromine (Raj *et al.*, 2020). It has been demonstrated that the application of seaweed extracts not only reduces fungal diseases but effectively promotes fertility and plant growth (Raj *et al.*, 2016). Phlorotannins were isolated from the brown seaweeds: *Fucus spiralis, Gongolaria. usneoides* (formerly *Cystoseira usneoides*) and *Gongolaria nodicaulis* (formerly *Cystoseira nodicaulis*) (Gomes *et al.*, 2022). The fatty acids, polysaccharides and phenolic compounds (phenol tannins) present in the crude extracts of brown and red seaweeds, effectively controlled post-harvest fungal diseases (Corato *et al.*, 2017).

2.1.1 Combating plant diseases by using *A. nodulosum*

The most studied and economically exploited species in brown algae was *A. nodulosum* (Garte *et al.*, 2006). *A. nodosum* when tested in greenhouse cucumber reduced *Phytophthora melonis* infection (Abkhoo and Sabbagh, 2016). Under nursery conditions, using VAM combined with seaweed extract reduced the *Fusarium* wilt of cavendish banana and improved plant growth (Ubaub and Poblacion, 2016). Extracts derived from the (brown seaweed) *A. nodosum* induce resistance against *Fusarium oxysporum* f.sp. *radicis-lycopersici* in tomato (Panjehkeh and Abkhoo, 2016). Downy mildew was decreased when *A. nodosum* extract was applied to onions (Dogra and Mandradia, 2012). The ability of primary and secondary clubroot infection produced by *Plasmodiophora brassicae* is reduced by the seaweed extract *A. nodosum*. It also considerably lowers the incidence of white blister disease on broccoli leaves, which is caused by *Albugo candida* (Wite *et al.*, 2015). *Fusarium graminearum* causes Fusarium-head blight (FHB), which can be prevented with the combination of liquid seaweed extract made from *A. nodosum* (Acadian sea plants) with chitosan. This is achieved by promoting the expression of genes linked to pathogenesis (*TaPR1, TaPR2, TaPR3, TaGlu2*) and defense-related enzymes (Gunupuru *et al.*, 2019). When plants were treated with seaweed extracts, the level of activity of a range of defense-related enzymes comprising chitinase, β-1, 3 glucanase, phenylalanine ammonia-lyase, peroxidase and polyphenyl oxidase increased drastically (Solanki *et al.*, 2011). An extract (0.2 per cent) from the seaweed *A. nodosum* (SW) was sprayed on carrot plants cultivated in greenhouses. The results indicate a considerable rise in the activity of several defense-related enzymes, such as peroxidase (PO), polyphenol oxidase, phenylalanine ammonia-lyase, chitinase and b-1,3-glucanase (Jayaraj *et al*., 2011).

2.1.2 Managing plant diseases using *Sargassum*

One of the largest genera of brown algae used as a biofertilizer in agriculture is *Sargassum* (Raj *et al*., 2018). Asnad *et al*. (2014) reported that the ethanolic extract of *Sargassum tenerrimum* when tested under agar well diffusion and disc diffusion method effectively controlled *Fusarium solani* and *F. oxysporum*. The methanolic extract of the brown seaweed *Sargassum wightii* functions bioactively against *Xanthomonas oryzae* pv. *oryzae*, which causes rice blight (Arunkumar *et al*., 2005). The antibacterial properties of *S. wightii* and *Padina gymnospora* against both Gram-positive and Gram-negative bacteria have been reported by (Kannan, 2019). The methanol extract of *Sargassum myricocystum* at 30 per cent concentration showed significant antifungal activity against soil-borne pathogens *Rhizoctonia solani* and *Macrophomina phaseolina* under *invitro* conditions (Sujatha *et al*., 2014).

The methanolic extract of *S. wightii* has the strongest effectiveness against the leaf spot infections caused by *Pseudomonas syringae* on *Gymnema sylvestre*. *In vitro* experiments showed that a 10 per cent concentration of *S. myricocystum* ethanol extracts effectively regulated and prevented the development of mycelial colonies of *Colletotrichum falcatum* in sugarcane (Ambika and Sujatha, 2015). The methanolic extract of *Sargassum cristaefolium* exhibited the highest inhibition of mycelial growth (73.00 per cent) under aseptic conditions on twister blight disease in onion crops (Mahalakshmi *et al*., 2024). The pathogen *Fusarium oxysporum* f. sp. *udum* in pigeon pea was shown to be significantly inhibited by the liquid seaweed extract of *S. myricocystum.* The lowest mycelial growth was observed at 24, 48, 72, 96 and 108 h after incubation under *in vitro* conditions (Ambika and Sujatha, 2014). The Pythium leek disease caused by *Pythium aphanidermatum* could be suppressed by an aqueous extract from *Sargassum vulgare* (Ammar *et al*., 2017).

When applied to the onion, the aqueous extract of *S. myricocystum* showed strong antifungal action against the pathogen *Alternaria porri* with the lowest mycelial growth (Ambika and Sujatha, 2015). Under *in vitro* conditions, the efficacy of seaweed extract *S. wightii* against the mycelial growth of *M. phaseolina* was controlled at different concentrations by poison food technique at 72 h after incubation (Somasundaram *et al.*, 2023). *M. phaseolina* in pigeon pea was successfully inhibited by the extract of *S. myricocystum* using the Poisson food technique, with the lowest mycelial growth of 61.5 mm at 96 h after incubation (Ambika and Sujatha, 2015). The dry root (*M. phaseolina*) of redgram was more easily controlled by the ethanolic extracts of *Sargassum polycystum* and *Hydropuntia edulis* (Ambika and Sujatha, 2014).

2.1.3 *Laminaria in* plant disease control

Laminaria belongs to the phylum Phaeophyta. The brown algae *Laminaria digitata* stimulated the plant defense system against a variety of diseases, for instance, *Botrytis cinerea* and *Plasmapara viticola* in grapevine (Aziz *et al*., 2003). The *F. oxysporum* fungi may be best controlled at a lower concentration of 15 per cent (Begum *et al*., 2016). *L. digitata* contain laminarin polysaccharide, when separated possesses the ability to trigger plant defense mechanisms (Klarzynski *et al*., 2000).

Hydrolyzing sodium alginate isolated from *Laminaria hyperborea* in an acidic solution resulted in the production of oligoguluronates, which in turn elicited defensive responses against pathogenic bacteria present on the plant's thallus as well as an epiphyte referred to as *Laminariocolax tomentosoides*. To scavenge reactive oxygen species (ROS), a significant quantity of iodide was generated in *L. digitata* when these oligoguluronates caused oxidative stress (Kupper *et al*., 2002).

2.1.4 *Ecklonia* and *Cystoseira against* disease control

Ecklonia is commonly known as 'sea bamboo'. *E. maxima* effectively controlled root-knot nematode infestation in tomatoes and enhanced plant growth Febles *et al*. (1995). While applying *E. maxima* liquid extract Verticillium wilt has decreased which has been caused by *Verticillium dahliae*, in green pepper (Rekanovic *et al*., 2010). *Agrobacterium tumefaciens*, a bacterial pathogen causing crown gall disease, was significantly decreased by spraying aqueous seaweed extract from *Cystoseira myriophylloides* (Esserti *et al*., 2017).

2.2 Green algae against plant pathogens

The green seaweed belongs to phylum Cholorophtya. *Enteromorpha, ulva, chaetomorpha, codium and caulerpa* are the genera that include common green seaweed species (Miao *et al*., 2020).

2.2.1 Role of *Ulva* in managing the plant diseases

When compared to other species genus *ulva* has a higher growth rate and polysaccharide content (Stiger-Pouvreau *et al*., 2016). The necrotic lesions caused by *Alternaria solani* have been reduced by extracts of *U. lactuca* (green algae) (Hernandez-Herrera *et al*., 2014). *Penicillium expansum* and *B. cinerea* development in apples were inhibited by *U. lactuca* extract (Machado *et al*., 2019). The elicitors found in *Ulva* were extracted through hot water extraction and conferred immunity to *Medicago truncatula* against *Phytophthora parasitica* var. *nicotianae* by inducing the PR-10 element. Furthermore, *M. truncatula* was shielded from the fungus that causes anthracnose, *Colletotrichum trifolii*, by a foliar spray containing extract from *Ulva* sp. (Cluzet *et al*., 2004).

The biologically active compounds in the ethyl acetate fraction made from an liquid extract of *U. lactuca* prevented *Pencillium digitatum* caused green mold from growing, thereby reducing post-harvest losses in citrus (Salim *et al*., 2020). Bionanoparticles derived from *Ulva fasciata* exhibit a minimum inhibitory effect at 40.00 ± 5.77µg/ml concentration, preventing the growth of *X. campestris* pv. *malvacearum* within a 14.00 ± 0.58 mm Zone of inhibition (Rajesh *et al*., 2012). The extract from *U. lactuca* induced the JA-dependent signaling system, which provided resistance against *X. campestris* and *A. solani* infection in tomato (Ramkissoon *et al*., 2017). The application of ethanolic and aqueous extracts derived from *U. lactuca* resulted in a reduction of both the frequency and impact of *P. digitatum* (Salim *et al*., 2023).

2.2.2 Controlling plant diseases using *Caulerpa*

Caulerpa belongs to the phylum Chlorophtya. The green algae *Caulerpa racemosa* effectively controls *F. oxysporum*, which is primarily responsible for the fungal disease (Rajarajan and Selvaraju, 2014). The dry root (*M. phaseolina*) of redgram was more easily controlled by the ethanolic extracts of *C. racemosa* (Ambika and Sujatha, 2014). The dry root (*M. phaseolina*) of redgram was more easily controlled by the ethanolic extracts of *C. racemosa* (Ambika and Sujatha, 2014). *F. oxysporum* development in cotton was arrested when treated with hexane, chloroform and methanol extracts of green algae *Caulerpa scalpelliformis* and *Caulerpa veravalensis* (Sahayaraj *et al*., 2012).

2.3 Red algae in control of plant diseases

Red algae belong to the phylum Rhodophyta, it was a rich source of bromine (Raj *et al*., 2020). *Soliera robusta* a red algae, when applied in combination with *Pseudomonas aeruginosa,* showed better control of *F. solani* infection (Sultana *et al*., 2005). On detached tomato leaves, the antifungal activity of various red algae species was demonstrated against *B. cinerea* and studied to improve the biocontrol efficiency (Jimenez *et al*., 2011).

2.3.1 *Kappaphycus*: A red algae against the spread of plant pathogens

K. alvarezii, a red seaweed in the phylum Rhodophyta, is grown mainly to extract the phycocolloid carrageenan. K-sap is a commercial name given to a product obtained from fresh seaweed (Bindu and Levine, 2011). Antibacterial action was demonstrated by phenols isolated from the red algae K. *alvarezii* against pathogens such as *Pseudomonas fluorescens* and *Staphylococcus aureus* (Rajasulochana *et al*., 2012). Tomato plants developed systemic defensive responses against *M. phaseolina* in response to a foliar treatment of 5 per cent K-sap. It was discovered that the tomato plants treated with K-sap had increased expression of the defense-response gene. K-sap treatment increased the expression of SA-dependent PR-1, PR-3 coding chitinase and PR-5 coding osmotins by 2-fold, 4.5-fold and 1194-fold, respectively, Higher amounts of SA accumulation validated the increase in gene expression (Agarwal *et al*., 2016).

2.3.2 Control of plant diseases by using *Garcilaria*

The Genus *Gracilaria* belongs to the phylum Rhodophyta. Fatty acids, sterols, terpenoids and hydrocolloid polysaccharides are abundant in *Garcilaria* (Shukla *et al.*, 2021). Disease caused by the pathogens *R. solani*, *F. solani* and *M. phaseolina* was decreased in the cucumber plants were grown in the soil amended with the powder of *Gracilaria confervoides*. The plant pathogens *R. solani*, *F. solani* and *M. phaseolina* were demonstrated to be susceptible to the antifungal effects of organic components of the liquid extract produced from *G. confervoides* (Soliman *et al*., 2018). *Garcilaria serrulatum* induced both salicylic acid and jasmonic acid-dependent signaling pathways against the pathogens (Ramkissoon *et al*., 2017).

3. Algae derived bioactive metabolites

The primary polysaccharides found in the cell membranes of green seaweeds are ulvans, whereas red seaweeds include agarans and carrageenans. Bioactive compounds which are identified from seaweeds and their role in defense mechanisms are listed in (Table 1). Brown seaweed contains alginates, fucans and laminarin (Jiao *et al*., 2011). *Salmonella* spp. is highly susceptible to *Cladophora socialis* (Chlorophyta) acetone extracts. As a result of their high polyphenol content, over 90 per cent of the components in polar extracts obtained by polar solvent extraction (methanol, ethanol and acetone) have been demonstrated to have antibacterial activity (Gomes *et al*., 2022). Alginates are linear polysaccharides that are essential components of the cell wall of brown algae. Alginates are made up of β-D-mannuronate and α-L-guluronate residues connected by 1,4 glycosidic linkages. Alginates are studied for their potential commercial use in biological science, materials science, agriculture, food goods and medicine (Fertah *et al*., 2017; Zhang *et al*., 2020).

Carrageenan from red seaweeds consists mostly of alternating units of D-galactose and 3,6-anhydro-galactose, connected by α-1,3 and β-1,4-glycosidic connections. They are linear, somewhat hydrophilic sulfated polygalactans that promote growth and elicit the plant defense mechanism (Shukla *et al*., 2016). Sulfated polysaccharides known as ulvans are recovered from the cell walls of green seaweeds, namely from different species belonging to the genus *Ulva*, which constitute approximately 9-36 per cent of the dry biomass of the seaweeds (Kidgell *et al*., 2019; Lakshmi *et al*., 2020; Mantri *et al*., 2020).

Table 1: Elicitors from seaweed extract and their action in plant defense mechanisms

Macro-algae	Application of seaweed extract	Mechanism of action	Reference
L. digitata	Foliar spray	Production of a defense-related gene and the build-up of phytoalexins, chitinase and β-1,3-glucanase activities.	Aziz *et al*., 2003
L. digitata	Foliar spray	Defense responses in tea plants triggered by the herbivore *Empoasca* (Matsumurasca) *onukii*	Xin *et al*., 2019
Commercial	Foliar spray	Triggered a defense reaction against *Trichoplusiani* by changing the metabolism of glucosinolates	Sangha *et al*., 2011
F. spiralis, Bifurcaria sp.	Root soaking	Enhancement of the innate defensive mechanisms of date palm roots	Bouissil *et al*., 2020
E. maxima	Seed treatment	Promoting seedling development and strengthening plant tolerance to soil-borne disease Fusarium wilt in tomato	Righini *et al*., 2023
U. lactuca	*In vitro* assay	Antioxidant defense enzyme activity has been stimulated to reduce anthracnose in papaya	Chiquito-contreras *et al*., 2019

These seaweed polar compounds had an antimicrobial effect on yeasts, with *Candida albicans* exhibiting the highest susceptibility among the yeast strains tested. Phlorotannin also increased the activity of yeast cells mitochondrial dehydrogenases (Gomes *et al*., 2022).When oligo-fucans were applied to tobacco plants at a concentration of 0.2 mg·ml^{-1}, there was an increase in systemic salicylic acid (SA) concentration and improved resistance to TMV infection (Vera *et al*., 2011). *M. truncatula* plants treated with ulvans extracted from *U. fasciata* resulted in better expression of phenylpropanoid pathway enzymes coding genes like phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS), chalcone isomerase (CHI), chalcone reductase (CHR), caffeic acid O-methyltransferase (CMT) and isoflavone reductase (IFR) (Cluzet *et al*., 2004). Ekclon and phloroglucinol, which were separated from the brown algae *E. maxima*, were used to treat maize seeds in an experiment. The treated seeds were shown to have a higher rate of germination than the control (Aina *et al*., 2022).

Sodium alginate, derived from *Bifurcaria bifurcata* and *F. spiralis*, regulates PAL and polyphenol metabolism to elicit natural defensive responses in the date palm (*Phoenix dactylifera*) roots. When alginate-based elicitors were applied to the roots of the date palm, there was a significant increase in PAL activity (Bouissil *et al*., 2020). Seaweed extract can have a direct impact on disease-causing agents or indirectly stimulate the plant's defensive mechanisms shown in (Figure 3). Similarly, in the *Vitis vinifera* cell suspension, sodium alginate promoted the production of stilbenes and flavonoids, which are recognized to be important components of defense responses. It also stimulated the expression of PAL, cinnamate 4-hydroxylase and 4-coumarate: CoA ligase, stilbene synthase and chalcone synthase including the genes involved in their production (Xu *et al*., 2015). The role of seaweeds in disease reduction due to the presence of different bio-active compounds is listed in Table 2.

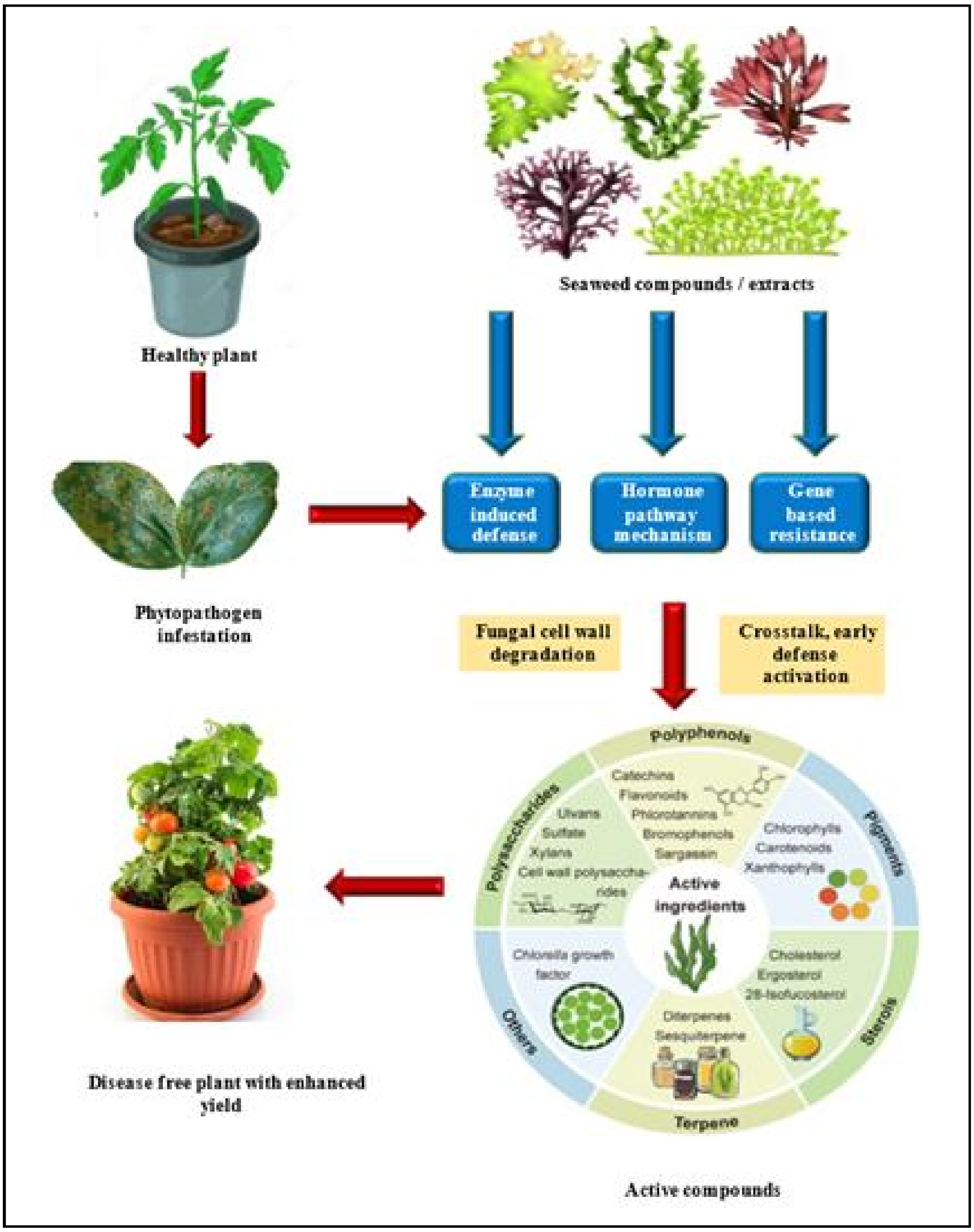

Figure 3: Illustration of potential ways by which seaweed extract may effectively manage diseases.

Table 2: Seaweed based disease management strategies in agriculture

Common name	Bioactive compounds present	Disease	Mode of application	Reference
Bladderwrack	Fucoidan	Powdery Mildew	Foliar application of seaweed extract	El-Sheekh *et al*., 2020
Rockweed	Phlorotannin	Downy Mildew	Soil amendment with seaweed powder extract	Johnston *et al*., 2023
Sargassum	Alginate	Bacterial Leaf Spot	Seaweed mulching	Garcia *et al*., 2020
Red algae	Carrageenan	Fusarium Wilt	Seaweed extract incorporated into soil	Chen and Wang, 2020
Irish moss	Carrageenan	Rhizoctonia Root Rot	Seaweed extract incorporated into compost	Liu *et al*., 2019
Kombu	Laminarin	Phytophthora Root Rot	Root drench with seaweed extract	Sharma *et al*., 2019
Sea lettuce	Ulvan	Powdery Mildew and Downy Mildew of grapevine.	Foliar application	Zarraonaindia *et al*., 2023
Sargassum	Alginate	Charcoal rot of tomato	Foliar spray of seaweed extract	Bosmaia *et al*., 2023

4. Plant growth promoter: Seaweed biostimulants

A wide range of growth responses were seen in plant growth when seaweed products (or extracts applied to foliage) were applied to the soil. The effects of seaweed extract on plants improved growth and development may be influenced by auxins, gibberellins, cytokinins, precursors of the cytokinins, betaine and ethylene that are present and might enhance the responses of plants to growth (Snedecor and Cochran, 1980). Growth of shoots and roots was encouraged by applying seeds and foliar fertilizer in combination, as well as by multiplying the frequency of foliar application (Matysiak *et al*., 2011).

These responses included effects on seed germination, seedling growth and plant growth parameters such as leaf number, leaf area, flower number, fruit number, fruit weight, plant height, root length, increased plant biomass and fruit yield and improved resistance to abiotic stresses, diseases and pests. Seaweed extracts were applied to the field and gave rise to increased crop production, seed germination and seedling growth (Craigie, 2011; Raj *et al*., 2018). Products made from seaweed might therefore be considered as biostimulants (Raj *et al*., 2020). The effects of growing tomato plants (*Lycopersicum esculentum*) in tropical fields with an alkaline seaweed extract obtained from *A. nodosum* (ASWE) have been studied by Ali *et al.* (2019). The number of flower clusters and individual flowers, the quantity of fruit, the dry weight of the leaves and roots and the length of the roots had been significantly boosted by the effectiveness of seaweed extract on tomato plants (Hashmath Inayath Hussain, 2021). Bean yield was boosted by 24 per cent when seaweed liquid extract was applied manually (Nelson and Van Staden, 1984). Onion plant growth and yield characteristics improved when seaweed extract *A. nodosum* was applied (Dogra and Mandradia, 2012).

4.1 Enhancing crop growth and productivity through seaweed extracts

Seaweed extracts are biostimulants derived particularly from brown and red algae. They can stimulate the development of crops, enhance the quality of crops, improve their tolerance to stress and boost soil health. Using various seaweed extracts in apples produced an array of beneficial effects on fruit yield, flowering and vegetative growth, along with some detrimental effects on the quality of the fruits while they were being stored (Raj *et al*., 2018). The crop's productivity and yield quality were enhanced by applying biostimulants based on seaweed extract. For example, adding *K. alvarezii* extracts to maize plants resulted in longer maize cobs and more seeds per cob (Trivedi *et al*., 2018). *Garcilaria dura* extracts treated the plants, resulting in a significant increase in wheat biomass that not only increased wheat's resistance to drought levels but also raised the yield (Sharma *et al*., 2019).

5. Conclusion

The efficiency and properties of seaweeds have made them an irreplaceable asset for attaining eco-friendly crop protection. The abundance of bioactive compounds, such as antioxidants, polyphenols and polysaccharides, present in seaweed entails its underlying potential to enhance plant immunity and combat against a range of diseases. Seaweed-based treatments can be applied to improve plant resistance, promote growth and lessen the negative impacts of diseases. Seaweed integration into agricultural systems shows its impact on efficient plant disease management strategies and sustainable agriculture as we continue to investigate their wide range of applications. Furthermore, seaweed extracts have been demonstrated as an environmentally acceptable substitute for synthetic chemicals, hence minimizing the dependency on traditional fungicides and pesticides to achieve the ideal toxic-free environment.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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