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ALGAL EXTRACTS AND THEIR IMPORTANCE IN PROMOTING PLANT GROWTH

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ABSTRACT:

The members of algae are groups of microscopic or macroscopic organisms with simple internal structures that generally live in oceans, moist soil, rivers, ponds, lakes and coastal areas. They are well demonstrated to be admirable natural bio-reserves of bioactive compounds and act as bio-fertilizers, plant growth promoters, anti-herbicides, bio-stimulators and confer tolerance to biotic and abiotic stresses. In the changing agro-climatic conditions and side effects associated with the use of chemical fertilizers, algae-based extracts form a green sustainable source of nutrients and compounds that can elicit phytostimulatory activities. The incorporation of algae-based extracts in crop health management and increasing yield will have a drastic effect on cultivation practices in a sustainable way. Because the algal extracts have multifunctional bio-inoculants that are of plant origin mimicking plant biology. The objective of this review is to get insight into the nature, type and mode of action of different algal extracts in plant growth promotions. This review noticed that different species of Phaeophyta, Rhodophyta, Chlorophyta and Cyanobacterial extracts have phytostimulatory activities. Of which, Phaeophyta aqueous extracts showed a potent application in plant growth promotion and cyanobacteria species contained high anti-pathogenicity along with biotic and abiotic stress tolerance. Interestingly, Rhodophyta species promoted plant growth by symbiotic association with fungi. Although this review reports the role of algal extracts on phytostimulatory activities, the mechanistic basis for the observed activities needs to be unearthed which forms the future scope of studies.

Keywords: Algae, Seaweed liquid extractions (SLEs), Foliar application (FA), Phyto stimulatory activities, Plant growth promotion and Sustainable agriculture.

1. INTRODUCTION

The inorganic fertilizers formed the basis for controlling insects and pests associated with plants and increasing plant yield. The end of the 19^{th} century witnessed the high use of inorganic fertilizers due to which they have become very expensive and reduced soil health causing environmental pollution. As a result of that, the sources for alternative sustainable and environmental friendly fertilizers were investigated. The use of organic bio-stimulants and biofertilizers was found to be vital in inducing nutrient absorption and plant growth production with high environmental resilience (Sunarpi et al. 2020). Employing natural bio-stimulants has become an alternative option for reducing the usage of inorganic fertilizers and increasing yield (Ivana et al. 2020). They are easy to extract, cost-effective, non-pollutant, non-toxic and contain natural bioactive compounds (Huda et al. 2018; Nidhi et al. 2021; Veeranan et al. 2018). Many investigations have revealed that Baltic brown and green algae contain macro and micro elements, phytohormones and polyphenolic compounds which make them potential biofertilizers, that enrich soil organic matter (Izabela et al. 2016; Godlewska et al. 2016; Asma et al. 2013; Omezzine et al. 2009; Reeta et al. 2011; Veeranan et al. 2018; Jebasingh et al. 2015). Many algal species induce protection against numerous pathogens in plants (Rosalba et al. 2014).

Seaweed liquid extracts (SLEs) gave fabricated support with fertilizer properties along with water retention and biodegradability activity and served as an alternative to synthetic materials and inorganic fertilizers (Chbani et al. 2013). Algal supplements are excellent reservoirs for bioactive compounds to ameliorate different aspects of nutrition and potentially improve crop productivity and protect against various types of abiotic stress (Ibrahim et al. 2014; Mohamed et al. 2020; Sandra et al. 2021; Stasio et al. 2018). The algal extracts have become an alternative to phytohormone-based inorganic products that act as cellular protectors and plant growth stimulators that are cost-efficient and eco-friendly. Multilayer forming with algal cultures enhances CO_2 fixation and increases the yield in crops (Mallikarjuna et al. 2020). The algae-associated inoculants may act as Plant Growth Promoters (PGPRs) and improve the implantation of species of economic interest and increase the yield under adverse conditions like drought and salinity. Algae can be grown in any area with less inputs of cost, energy and manpower. They offer a very important option for agriculture and livestock feed in many countries where soil health has become a limiting factor (Julia et al. 2020).

Algae have become a renewable source for the sustainable production of bioactive compounds and are rich sources of PUMFs, polysaccharides having antioxidants, antifungal, antibacterial, antifungal, antiviral, antioxidant, anti-inflammatory, and anti-tumoral activities (Izabela et al. 2014). In addition to this, different plant (bio-fertilizers, bio-stimulants and bio-regulators reports), animal (feed additives) and human-centric beneficial activities (food, cosmetics, pharmaceuticals, biofuels, biodegradation, phytoremediation and phyto stabilization) are known to be displayed by algal extracts (Izabela et al. 2014). In this review, we have summarized the studies of algal extracts on plant growth promotion carried out till now. In addition to this, we are also reporting anti-pathogenic activity, mycorrhizal association with endofungal species and their stress tolerance properties.

2. Seaweed liquid extraction preparation

The unique composition and possibilities of a wide range of applications of algal SLEs are gaining attention in traditional agriculture. Up to now researchers have discovered many ways based on enzymes, microwave, pressurized liquid, supercritical fluid and ultrasound-assisted extraction methods to extract biologically active compounds without degradation of their activities (Izabela et al. 2015). Most commercial algal extracts are obtained from brown algae by alkaline hydrolysis, pH and temperature. High pH and temperature favour the synthesis of alginate and polysaccharides. At pH 11 and 80° C extractions showed root promotion activity whereas extractions carried at pH 12 and 80° C enhanced seedling growth (Domínguez et al. 2014). The ultrasound-assisted extraction method is beneficial for increasing extraction yield, total phenolics and high antioxidant activities from different algal species (Rubén et al. 2018). Moreover, the antioxidant activities of the polysaccharides obtained after hot-water extraction were higher than those of other polysaccharides (Cheng et al. 2013).

3. Algal extracts promote plant growth

Algal extracts stimulated the plant growth at low concentrations but at high concentrations showed negative results on seed germination and lateral root formation (Prasanth et al. 2007; Nidhi et al. 2021; Anil et al. 2017; Fatemeh et al. 2018; Satish et al. 2014). The Gracilaria edulis, Sargassum wightii Caulerpa scalpelliformis, and Gracilariacorticate aqueous extracts fortified medium were used for maturation and germination of somatic embryos in tomato (Vinoth et al. 2012, 2014). Macrocystis pyrifera extract enhanced tomato seedling growth, adventitious root formation in Vigna radiata (Dominguez et al. 2014) and root biomass in Lipidum sativa (Julia et al. 2020). The presence of several kinds of nutrients in brown and green algal species that stimulate the growth of Vigna mungo, Vigna radiata and Cajanus canjan (L.) was reported (Jebasingh et al. 2015; Bharath et al. 2018; Erulan et al. 2009). Induced augmentation of the nutrient’s uptake in winter wheat (Izabel et al. 2016) and enhanced seedling growth and photosynthetic efficiency in radish observed with (Godlewska et al. 2019) M.pyrifera administration. These results indicate that the above algal species are good biofertilizers that play an important role in the production of biofortified vegetables. The use of Cylindrospermum muscicola enhanced nitrogen fixation and stimulated the root growth in rice through by synthesis of inter-convertible auxin-like substances (Venkataraman et al. 1967). Similarly, brown and green algal species fix Nitrogen in maize (Safinaz et al. 2013), lettuce (Miceli et al. 2021; Puglisi et al. 2020) and tomato (Hussain et al. 2021), enhanced fertility at rhizosphere by increasing the available bacterial count to fix nitrogen into the soil. Similarly, thermo-acid extraction of Durvillaea antarctica enhanced biochemical activities and nitrogen assimilation in cucumber seedlings (Yongzhou et al. 2021). The use of aqueous extracts of C.vulgaris increased N, P and K quantity in leaves, fruit quality, TSS, TSS/ acid ratio, yield and decreased total acidity in grapes (Eman et al. 2008) and tomato (Sena et al. 2015).

Similarly, Cladophoropsis gerloffii and Sargassum johnstonii pre-plantation treatment showed a high level of moisture around seeds after dryness or leakage of ABA from the seeds, enhanced seedling and fruit quality (Titratable acidity and vitamin C) (Reeta Kumari et al. 2011; Huda et al. 2018). The brown alga, Sargassum cristafolium solid extract promoted the yield in rice by providing essential elements rapidly to the roots through the soil (Sunarpi et al. 2020). This kind of phenomenon has been reported earlier in different crops like maize (Safinaz et al. 2013), Lepidium sativum (Godlewska et al. 2016), rice (Sunarpi et al. 2019), soybean (Kocira et al. 2019), cucumber (Sunarpi et al. 2019) and tomato plants (Sunarpi et al. 2020). Ulva rigida, Codiumdecorticatum, Fucusspiralis, Bifurcaria bifurcate, Gigartina pistillata and Chondracanthus acicularis aqueous extracts have displayed water-holding capacity to promote seed germination in in-vitro. Further studies are required to understand the background behind the enhanced germination and assist the field-level performance of these extracts in tomatoes (Mzibra et al. 2018; Said et al. 2021). Sargassum wightii aqueous extracts induced integral chlorophyll biosynthesis, a role in augmentation for growth in cluster beans (Vijayanand et al. 2014). Similarly, Sargassum wightii, Turbinaria ornata and Caulerpa racemosa foliar application stimulated protein expression to enhance the absorption of necessary elements by the seedling at the time of germination in Ocimum sanctum (Veeranan et al. 2018). The Anabaena oryzae, Nostoc muscorum and Chlorella vulgaris methanol extracts acted as precursors for phytohormonal production and methanol extractions with other algae showed notable phenotypic characteristics (Walaa et al. 2022).

<table>
<tr><th>Division</th><th>Family</th><th>Plant growth</th><th>Stress</th><th>Antifungal</th><th>Symbiosis</th><th>antibacterial</th></tr>
<tr><td rowspan="4">Rhodophyta</td><td>Rhodophyceae</td><td>7</td><td rowspan="4"></td><td rowspan="4">5</td><td rowspan="4">2</td><td rowspan="4">1</td></tr>
<tr><td>Gigartinaceae</td><td>1</td></tr>
<tr><td>Corallinaceae</td><td>1</td></tr>
<tr><td>Solieriaceae</td><td>1</td></tr>
<tr><td rowspan="3">Pheophyta</td><td>Pheophyceae</td><td>11</td><td rowspan="2">7</td><td rowspan="3">7</td><td rowspan="3">1</td><td rowspan="3">6</td></tr>
<tr><td>Sargassaceae</td><td>1</td></tr>
<tr><td>Dictyotaceae</td><td></td><td>1</td></tr>
<tr><td rowspan="2">Cynobacteria</td><td>Cynophyceae</td><td>3</td><td>3</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">1</td></tr>
<tr><td>Oscillatoriaceae</td><td></td><td>1</td></tr>
<tr><td rowspan="5">Chlorophyta</td><td>Chlorophyceae</td><td>5</td><td>3</td><td>10</td><td>2</td><td>1</td></tr>
<tr><td>Ulvophyceae</td><td></td><td rowspan="3">3</td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td></tr>
<tr><td>Brypsidoophyceae</td><td>3</td></tr>
<tr><td>Cladophoraceae</td><td>2</td></tr>
<tr><td>Ulvaceae</td><td></td><td>1</td></tr>
</table>

Table 1. Family wise reports of plant promoting activities of Algal extracts.

4. Role of SLEs for biotic and abiotic stress tolerance

Algal extracts are known to be involved in nitrogen metabolism, enhanced photosynthetic efficiency (C-fixation, Rubisco and CAH activity) and accumulation of linolenic acid, a key precursor for the biosynthesis of jasmonate and niacinamide. It also stimulates the denovo synthesis of palmitic and stearic lipids. Similarly, Tetraselmis species stimulated the lipophilic metabolite that protects PSII against photodamage under abiotic stress (Joan et al. 2020). Fal et al (2023) recently reported that Aphanothece species enhanced monounsaturated fatty acid and saturated fatty acid synthesis and tolerance to Pb and Cd toxicity. The above study also reported increased phyto-stabilization activity in roots. This indicates that exposure of Aphanothece crude extract to plants alleviates the metal stress by enhancing antioxidant activity and nutrient status by active uptake and redistribution in different plant parts. Similarly, Coccomyxa chodatii SAG 216-2 deprived with N or P reduced Hg accumulation by extracellular precipitation, biosorption of cell wall, decreased uptake or increased efflux in wheat seedlings with Hg and abiotic stress (Mona et al. 2023).

Likewise, Dictyota dichotoma extract reduced As (arsenic) concentration in grain and increased nutritional quality and rice grain shape (El-katony et al. 2021). Algal extracts showed antioxidant activity against herbicide toxicity, increased metabolic rate in wheat (Gaffar et al. 2022) and induced protection in faba seeds under stress (Osman et al. 2016). In the case of sugar cane, drought stress can be adapted by carbohydrates induced with Ascophyllum nodosum foliar application under unfavorable conditions (Lucas et al. 2022). Also, A.nodosum derivatives acquire bioactive compounds under osmotic conditions (Emilio et al. 2017) and tolerance to Fe deficiency in tomatoes (Sandra et al. 2021).

Foliar application of Sargassum denticulatum overcomes the severity of drought in wheat by improving antioxidants, stability of proteins and diversity of non-coding cp-DNA regions (trnL and psbA-trnH without deletion) (Ali et al. 2022). Macrocystis pyrifera extracts increased root biomass in Lepidum sativumto overcome the drought conditions (Julia et al. 2020). But contrastingly, Capsosiphon fulvescens, Enteromorpha linza and Monostroma nitidummethanol extracts act synergistically for inhibition of L.sativa seed germination (Choi et al. 2014). Cystoseira mediterranea (Sauv.) aqueous extracts restored seed germination by reducing the ROS production and leakage of electrolytes that in turn protected the membrane integrity of seedlings under salt stress in barley (Leila et al. 2021). Recently it was reported that (Jafarlou et al. 2023) Sargassum angustifoliumsea weed extracts treated with Calotropis procera (Aiton) showed moderate tolerance to salinity by preventing the proline oxidative degradation and downregulation of catabolism of proline by PRODH gene. It is involved in P5CS gene expression for the biosynthesis of proline against deleterious effects of drought stress (Shahriari et al. 2021).

Likewise, Lessonia nigrescens polysaccharides increased superoxide dismutase, peroxidase activity and downregulated the TaHKT 2;1 expression in roots and upregulated antiporters functioning in the exclusion of sodium to vacuoles that reduced sodium accumulation in the soil and Na^+/K^+ in leaves (Zou et al. 2019). Ulva lactuca pre-soaking, detoxified the H_2O_2 to mitigate salt stress for improving saline-alkali tolerance in wheat (Ibrahim et al. 2014). Sargassum wightii and Padina gymnospora reduced ROS production and Na^+ accumulation and maintained the equilibrium between K^+/Na^+, Ca^{2+}/Na^+, and Mg^{2+}/Na^+ ions under salt stress in Abelmoschus esculentus L. (Zawar Khan et al. 2022) and Lycopersicon esculentumL. (Rosalba et al. 2022). Sargassumhydro chloric extract enhanced seedling growth and antioxidant activity under salinity indicating that SLEs can be an alternative to inorganic inducers against the negative effects in tomatoes (Oscar et al. 2022). Chlorella ellipsoida and Spirulina maxima foliar application increased photosynthetic efficiency and antioxidants in Triticum aestivum L. cv.Giza 94, cultivated with seawater (10 and 20 v/v). These results indicate that irrigation of plants with brackish water is possible with algal extracts for maintaining osmotic balance (Hanaa et al. 2008). The studies involving Corallina elongate foliar application revealed that it enhances antioxidants and existence under drought in wheat followed by Sargassum latifolium along with two commercial seaweed products (Canada powder and Oligo-X) (Alharbi et al. 2022). Based on the above results, it can be concluded that seaweed liquid extracts confer tolerance to plants under abiotic stress.

5. Algal extracts enhance the microbial symbiosis relationship with plants

C^{13} NMR studies on Ulva fasciata SLEs indicated that it controls the anthracnose disease induced by Colletotrichum lindemuthianumin bean. Contrastingly in against to this activity, it promotes the mycelium growth and conidia formation of the fungus in in-vitro. These results indicate that SLEs can play an important role in plant growth or pathogen interactions (Paulert et al. 2009). Several kinds of algal species like, Gracilaria verrucosa, Gelidium amansii and Eucheuma cottonii and Chlorella pyrenoidosa enhance the arbuscular mycorrhizal root colonization in papaya and passion fruit. It seems that algal extracts enhance the symbiosis of AM fungi with plants (Kuwada et al. 2006). Aschophyllum nodosum foliar application enhances spore germination, hyphal growth and elicits the protection indirectly under stress when it is associated with Rhizophagus irregularis.

This result of algal extracts is promising in promoting the interdependent relationship of AM fungi with higher plants through plant microbe symbiosis which will enormously affect agriculture production. This is the environmentally sustainable green technology offered by very cheap raw materials of algal extracts (Sarah et al. 2021).

6. Antibacterial efficacy of algal extracts

The boiled extracts of Polysiphonia, Ulva, and Cladophora glomerata from the Baltic Sea inhibited the E.coli activity (Godlewska et al. 2016). In another study on Lessonia trabeculata it inhibits the Botrytis cinereal growth by reducing the number and necrotic lesion size on tomato leaves. The Gracillaria chilensis aqueous and ethanolic extracts prevented the Phytophthora cinnamomic growth depending on the dose and time of collection of samples (Jimenezet al. 2011). Similarly, Durvillaea antarctica ethanol extract showed moderate resistance to tobacco mosaic virus, whereas aqueous extract (AEs) of the same alga is more effective against TMV irrespective of the season.

These results suggest that macroalgae contain bioactive compounds with several chemical properties needed for controlling the pathogen activities in different crops. Siham et al (2017) for the first time reported that Cystoseira myriophylloides and Fucus spiralis AEs have significantly reduced the crown gall disease in tomatoes by enhancing their H_2O_2 concentration in cells after infection by staphylococcus aureus, Enterococcus faecalis, Pseudomonas aeruginosa, Klebsiella pneumonia, and Bacillus subtilis. The said extract had moderate antibacterial activity against E.coli, Pseudomonas fluorescens and Streptococcus agalactiae.

A recent study (Mofida et al. 2023) demonstrated that methanolic extracts of Padina pavonica L. showed resistance to E.coli, Pseudomonas fluorescens and Streptococcus agalactiaegrowth. Likewise, ME and ASEs from Sargassum species showed antibiofilm potency along with antimicrobial activity against Staphylococcus aureus (Mousa et al. 2023). High altitude algal species, Arthrospira platensis HANL01 MEs controlled E. coli, E. albertii,P. aeruginosa, Pseudomonas fluorescence, Salmonella typhimurium and Shigella dysenteriae growth. The results of these studies can be exploited in the future for drug development studies, particularly against multi-drug-resistant bacteria (Ritu et al. 2023).

Name of the plant	**Algal species**	**Extract**	**Experiment condition**	**Mode of application**	**Effects of algal extracts**	**References**
Tomato	Durvillaea potatorum and Ascophyllum nodosum	Aqueous extract	Green house condition	Soil application	Enhanced biomass, quality and nitrogen availability.	Hussain et al. 2021
	Ulva rigida, Codium decorticatum, Gigartina, Chondracanthusacicularis, Fucus spiralis and Bifurcaria bifurcate	Ethanolic extraction	Green house condition	Soil application	Increased seed germination, biomass and chlorophylls.	Mzibra et al. 2018
	Chlorella vulgaris	Aqueous extract	Green house condition	Soil, liquid and foliar application	Increased plant growth, yield and some fruit quality.	Sena et al. 2015
	Rygex (R) and Super Fifty (SF)	Aqueous extract	Green house condition	Soil application	Improved nutritional values in salinity condition.	Stasio et al. 2017
Maize	Corllina elongate, Corllina Officinallis, Jania rubens and Ulva facsiata	Aqueous extract	In vitro condition	Foliar application	Improved seed germination, seedling vigor, photosynthetic activity and plant growth.	Fayzi et al. 2020
Wheat	Ulva lactuca	Aqueous extract	Lab condition	Seed soaking	Enhanced germination percentage, seedling growth and antioxidant content under salt stress.	Ibrahim et al. 2014
	Polysiphonia, Ulva and Cladophora	Supercritical fluid	Lab condition	Foliar application	Improved photosynth	Izabela et al.

		extraction			etic activity and root thickness.	2016
Rice	Oscillatoria acuta, Plectonema boryanum	Aqueous extract	Lab condition	Extraction suspension	Growth promotion and stress tolerance.	Dhananjaya et al. 2011
Brinjal	Gracilaria salicornia, Padina gymnospora,Padina boergesenii, Gelidiella acerosa	Aqueous extract	In vitro condition	Supplemented with medium	Increased seedling growth and multiple shoot proliferation.	Satish et al . 2014
Radish	Spirulina platensis	Aqueous extract	Lab condition	Pre-plantation, foliar spray and homogenate extract	Improved aerial parts, photosynthesis and biomass.	Godlewska et al. 2019
Lettuce	Scenedesmus quadricauda	Aqueous extract	Lab condition	Not mentioned	Promote plant growth and secondary metabolites.	Puglisi et al. 2020
	Ecklonia maxima	Not mentioned	Greenhouse condition	Root application	Avoid nutrient enzymes leakage and water loss. Delays the leaf senescence and increase the shelf-life.	Miceli et al. 2021
Bean	Ulva fasciata	Methanolic extract	Greenhouse condition	Foliar application	Promotes the growth.	Paulert et al. 2009
Black gram	Laurencia pinnatifida, Surgassum duplicatum and Caulerpa scalpelliformis	Aqueous extract	Lab condition	Foliar application	Promote the growth, increased photosynthetic activity	Jebasingh et al. 2015

					and totalprotein concentration.	
	Sargassum polycystum	Aqueous extract	Lab condition	Soil application	Increased yield and biochemical activities	Bharath et al. 2018
Mulberry	Ascophyllum nodosum	Aqueous extract	Field condition	Foliar application	Increased quality and quantity of leaves.	Anil et al. 2017
Moth bean	Ascophyllum nodosum	Aqueous extract	Lab condition	Foliar application and root application	Enhanced growth and yield.	Nidhi et al . 2021
Red gram	Sargassum polycystum	Aqueous and ethanolic extract	Not mentioned	Pre-plantation treatment	Increased seed germination, growth, biochemicals and photosynthetic efficiency.	Erulan et al. 2009

Table 2. Summary of the role of effect of some algal / seaweed extracts on plant growth promotion.

7. Antifungal properties of algal extracts

Aqueous extracts of different algal species like Scenedesmus obliquus, Nannochloropsis, Phaeodactylum tricornutumand Spirulina significantly reduced the phytopathogenic activities of Sclerotium rolfsii, Rhizoctonia solani and Botrytis cinereal (Benjamin et al. 2022). Similarly, Padina pavonica (L.) strongly inhibited the Fusarium graminearum, Penicillium expanse and Alternaria alternata activities and acted as a biofertilizer without deteriorating the physio-chemical properties of the soil (Faten et al. 2009). Most of the algal extracts enriched with ulvans, alginates, fucans, and laminarans (β-1,3 glucan) have induced resistance to three powdery mildew pathogens (Erysiphe polygoni, Erysiphe necator and Sphareotheca fuliginea) in bean, grapevine and cucumber. The reproducibility and antifungal activities of ulvans against pathogens prove that they are an impactable defense system to control fungal disease in plants (Jaulneau et al. 2011). Sargassum fusiforme extract acts as an elicitor and induces hypersensitivity and O^{-}_{2} accumulation in leaf tissues to activate the resistance to late blight, grey mold and powdery mildew diseases in tomatoes (Sbaihat et al. 2015). Similarly, Padina gymnospora and Sargassum liebmannii triggered defense system-induced protection against the necrotrophic fungus Alternaria solani in tomato (Rosalba et al. 2014). Pomegranate mixed with U. lactuca extract showed severe devasting effects on mycelial growth and conidia formation in Alternaria species (Hassan et al. 2023). Similarly, Jania adhaerens ASEs can protect seedling emergence and plant development of tomatoes against soil-borne pathogens like Rhizoctonia solani, Pythium ultimum and Fusarium oxysporum (Hillary et al. 2022). Ulva fasciata, Enteromorpha flexuosa (Mostafa et al. 2021) and Gracilaria confervoides chloroform extracts prevent soil-borne fungi like Rhizoctonia solani, Fusarium solani and Macrophomina phaseolina. G.confervoides malformatesthe M.phaseolina areal mycelium and microsclerotia in cucumber (Soliman et al. 2018). Likewise, Nostoccommune methanol extract (Kim et al. 2008) and Fucus vesiculosus L. supercritical fluid extract (Katarzyna et al. 2019) reduce the conidia formation and sporulation of Fusarium oxysporum and Fusarium culmorum for control of wilt disease in tomato. Several green microalgal species, U .lactuca, Chlorella vulgaris, Chlorella minutissima, and Chlorella protothecoides strongly prohibit the activities of Aspergillus niger, Alternaria and Penicillium expansum that cause soft rot fungal disease in apple (Meyrem et al. 2019). Olivieri et al (2023) recently reported that Undaria pinnatifida AEs act as an inducer of resistance to Phytophthora infestans in potatoes and inhibit the growth in in-vitro. According to Abla et al (2023) studies, macroalgal extracts of Halimeda opuntia, Turbunaria decurrens and Jania ruben act as a bio-controller agent to protect food against fungi and inhibit the growth and production of four types of aflatoxins. This study reveals the possibility of using algae for the production of natural fungicides.

It also affirms that by increasing the utilization of algal extracts for food production with natural algal fungicides in pharmaceutical and food production industries a circular bio-economy be generated. The above data on algal extracts sheds light on how they can be used as bio-control agents in postharvest management and food preservation against fungal pathogens.

Figure 1. Ideal image highlighting the positive impacts of seaweed extracts (Foliar and solid applications) in plantlets.

8. Cultivation of Algae

The above experimental evidence indicates that algae and algae-based products and processes represent a viable alternative for sustainable green technologies. However, these experiments are conducted in small-scale setups that are not suitable for large-scale commercial production. Hence, there is an extensive need for scaling up for large-scale production of algae. There are many cultivation practices for small and large-scale cultivation of algae like Spirulina, Sargassum, Scenedesmus, chlorella vulgaris and Fucus.

The thermal evaporation of water is less in open ponds than in tubular bioreactors and closed photobioreactors (Soniet al. 2017) and it is moderately inexpensive and concludes lower initial capital expenses to build, grounded on favorable features with suitable algae growth. At this juncture, it should be noted both soil and water qualities are important to evaluate the viability of different kinds of algae species with high biomass cultivation for bio-fuel and food production. The cultivation of algae demands less energy, soil and water than traditional methods used for the production of plants and animals. The algae are very cheap raw materials that can be isolated from any place and can be grown in diverse habitats like municipal seepage water, brackish water, seawater, eutrophicated areas, industrial wastes and exhausts, etc. (Singh et al. 2011).

9. Summary:

Based on the current data, it can be summarized that a wide range of algal species display activities like plant promotion, anti-pathogenicity, and stress tolerance with different types of extracts. The marine algal species have biologically active compounds (like PUFAs, antioxidants and polysaccharides) that deliver plant growth promoters, anti-stress, phytodegradation, antifungal, antibacterial and anti-herbicidal activities having a role in agriculture production. Incorporation of cheap, readily available and easily cultivated algae with Phyto stimulatory activities will reduce the economic burden on the farming community increase soil fertility and reduce pollution-related problems.

10. Future prospective:

Many small unanswered questions and doubts have been listed below; they may form the basis for future scope of work.

1. Why SLEs are showing positive results at low concentrations? How we can utilize highly concentrated extracts in agriculture applications?
2. How to overcome limitations in large-scale production of different algae verities polysaccharides with affordable cost to the farmers.
3. Will these algal extracts serve as an antioxidant-rich source of food material to people?
4. Can we develop bio-fortified vegetables and food grains without any gene modification using algal extractions?
5. Can we generate desalting plants by using algal species, which will reduce salinity in alkaline soils?
6. There is a possibility of developing High CO2-required plants from different algal species for more yield in food crops and decreasing the carbon emission to climate.
7. The algal extracts can also be used to develop antibiotics and multivitamin products for human consumption.
8. Understanding the interaction of algal extracts with rhizobium bacteria will help increase nitrogen fixation in plants for sustainable agriculture development.
9. High-concentrated SLEs act as a weedicide, so natural weedicide development can be tested.
10. There is an extensive need for the popularization of potential applications of algal extracts, and their safety and efficacy issues to the general public and specifically to the planning community to achieve the targets of sustainable green technology through a circular bio-economy approach.

11. There is a need for extensive screening of algae to serve as cheap bio resource material for pure compounds across different classes of algae and to elucidate their industrial importance.

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