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REVIEW PAPER

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Review on Seaweed based valuable products and their applications

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Abstract

Seaweeds are vital resources with economic, societal, and environmental values. These are inhabited in different climatic zones of the oceans. The major factors affecting seaweed distribution are temperature, tidal height, salinity, sea level rise, carbon dioxide (CO_2) concentration, and ultraviolet (UV) radiation. Typically, seaweeds are considered a critical source of bioactive compounds that have broad applications in food, cosmetic, medical, and agricultural fields. Presently, nanomaterials are gaining more attraction in medicine, environment, and food and cosmetic industry. Several metallic nanoparticles (silver and gold) are synthesized from seaweeds. The yield of the bioactive compounds mainly depends on the seaweed species and the extraction method employed. Hence, updated knowledge on these aspects is required for further research. Based on the research outcomes published in journals indexed in Scopus, Web of Science, and regional journals, this review addresses (a) the extraction of bioactive compounds present in seaweeds, (b) the applications of the bioactive compounds obtained from seaweeds, (c) synthesis and applications of biochar and nanomaterials, and (d) application of seaweed extract for crop growth.

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Introduction

Seaweeds /marine algae are primitive non-flowering photosynthetic macrophytes present in tidal regions of the oceans; approximately 25,000 to 30,000 species have been identified yet (Santos *et al.*, 2015) and are considered as natural renewable resources. Seaweeds are commercially exploited as they are fast growers, without the need for fertilizers in comparison to terrestrial plants (Lorbeer *et al.*, 2013). Due to the growing demand for marine-based commodities, seaweed cultivation has become one of the leading occupations (Eggertsen and Halling, 2020). It is estimated that about 23.78 million tons (fresh weight) of seaweed was produced during 2012 by aquaculture (Rao *et al.*, 2018). Presently, seaweed cultivation is being practiced in >50 countries, and 28.5 million tons of seaweed and other algae were harvested in 2014. The harvested seaweeds are directly consumed or used as a starting material to produce commercially important products such as hydrocolloids and fertilizers (FAO, 2016). The major hydrocolloids extracted from seaweeds such as alginate, carrageenan, and agar have wide applications in food, pharmaceutical, and biotechnological industries with a market value just above USD 1.1billion (Rhein-Knudsen *et al.*, 2015). Thus, the research on seaweeds and their application have come a long way rapidly (Critchley *et al.*, 2020). Although the distribution and commercial applications of seaweeds have been explored globally, several constraints are faced while gathering the data. Hence, this review highlights the current status of research in seaweed, and the applications.

Critical compounds extracted from seaweeds

Seaweeds are rich in protein, amino acids, inorganic salts, vitamins, alginate, enzymes, plant hormones, polyphenols, and polysaccharides (Manimuthu *et al.*, 2015). However, the bioavailability of the organic matter in seaweed biomass is limited by its structural intricacy and the inflexibility of its particles resulting in inefficient degradation (Jung *et al.*, 2015). The seaweed species, *Chaetomorpha antennina*,contains an organic content of proteins, carbohydrates, and lipids (Premalatha *et al.*, 2011). *E. intestinalis* contains natural astaxanthin, used as a dietary supplement for improving the quality of tiger shrimp (*Penaeus monodon*) (Mondal *et al.*, 2015). Moreover, critical products, such as proteins, fatty acids, steroids, carotenoids, phycocolloids, microspotine-like aminoacids, halogenated compounds, and polyketides, are derived from marine-based microalgal species (Rengasamy etal.,2020). The bioactive compounds are present as storage polysaccharides in the cell wall of seaweeds. However, the types of compounds produced are species-dependent (Holdt and Kraan, 2011), and those in the different groups of seaweeds are listed in Table 1.

Table 1. Bioactive compounds produced by different algal species.

Algal type	Pigment	Examples	Bioactive compounds
Green algae	Chlorophyll	*Ulva* sp., *Valonia* sp., *Caulerpa* sp., *Halimeda* sp.	Sulphuric acid polysaccharides Sulphated galactans, xylans
Brown algae	Yellow-brown pigment over chlorophyll (fucoxanthin)	*Laminaria* sp. *(kelps) Fucus* sp. *Sargassum* sp., *Ascophyllum* sp., *Macrocystis* sp.	Alginic acid, fucoidan(sulphated fucose, laminarin, β-1,3 glucan, sargassan
Red algae	Red (phycobillins)	*Palmaria* sp., *Chondrus* sp.	Agars, Carageenans, xylans, floridean, starch(amylo-pectin like glucan), water-soluble sulphated galactan, porphyran as mucopolysaccharides located in the intracellular spaces

(Kumar *et al.*, 2008; Murata and Nakozoe 2001; Goh *et al.*, 2012)

The critical bioactive compounds include polyphenols (Mhadhebi *et al.*, 2014), polysaccharides (Kwon and Nam, 2007), meroterpenoides (Valls *et al.*, 1993), and terpenoides (Culioli *et al.*, 2004). The bioactive compounds possess a broad range of biological activities, including anti-inflammatory, antibiotics, antiviral, cytotoxic, and antimitotic activities (Bhosale *et al.*, 2002; Smith, 2004).

Reportedly, the crude extract of *Sargassum* sp. carried sulfated polysaccharides with have anti-inflammatory activity, which could be attributed to the presence of fucoidan, a major constituent in the*Sargassum* sp. (Saraswati *et al.*, 2019). Furthermore, the alkaloid caulperin was isolated from the liquid extracts of *C. racemosa*, which has anti-inflammatory and anti-nociceptive activities (De Souza *et al.*, 2009). The chemical structure of bioactive compounds namely fucoxanthin, carotenoids, neoxanthin, zeaxanthin, astaxanthin, fucoidan, galactan, carrageenan, fucan, phlorotannins, and phloroglucocinol produced by seaweeds are given in

Table 2. Bioactive compounds of important seaweed species and their significance.

Bioactive compound	Seaweed species	Importance/ findings	Reference
Fucoidan	*F. vesiculosus, L. digitata, F. evanescens, F. serratus, A. nodosum, Pelvetia canaliculata, Cladosiphon okamuranus, S. fusiforme, L. japonica, S. horneri, Nemacystus decipiens, P. gymnospora, L.a hyperborea E. prolifera*	anti-oxidant, anti-tumor, anti-coagulant, anti-thrombotic, immunoregulatory, anti-viral and anti-inflammatory	Luthuli *et al.*, 2019
	L. guryanovae	Anti- cancer	Lee *et al.*, 2008
	F. evanescens	Antitumor and antimetastatic	Li *et al.*, 2008
Not specified	*Colpomenia sinuosa*	Antioxidant	Lakameera *et al.*, 2008
Galactan Carrageenan	*F. vesiculosus* *Gigartina skottsbergii*	Anti- ulcer, antioxidant, antitumor, immunostimulatory, anti- inflammatory, pulmonary fibrosis, anticoagulant/antithrombotic, lipid lowering, antiviral, antibacterial, antiprotozoan, hyperplasia prevention, gastrointestinal, regenerative and nano medicine applications	Veena *et al.*, 2007; Barahona *et al.*, 2011
Polysaccharide (SFPS)	*S.* (Harv.) Setchel	Antitumour and immunomodulatory	Chen *et al.*, 2012
Not specified	*P. boergesenii*	Active against Carbon Tetrachloride (CCl_4) induced oxidative damage and liver fibrosis inrats	Karthikeyan *et al.*, 2010
Fucan	*Fucus* sp., *Sargassum* sp., *Laminaria* sp., *Undaria* sp., *Lessonia* sp., *Dictyota* sp., *Dictyopteris* sp., *Ascophyllum* sp, *Eclonia* sp., *Canistrocarpus* sp., *Lobophota* sp,*Turbinaria* sp., *Padina* sp., *Adenocystis* sp., *Sphacelaria* sp., *Cystoseira* sp.,	Anticoagulant	Costa *et al.*, 2011
Carrageenan	*Hypnea musciformis, Cryptonemia crenulata, Kappaphycus alvarezii* *Undaria pinnitafida* Gracilaria birdiae	Food additive, pharmaceutical and medical industry	Liu *et al.* 2015 Rhein-Knudsen *et al.*, 2017
	K. alvarezii, Euchema denticulatum	Drug delivery	Youssouf *et al.*, 2017
Ulvans	*U. pertusua*	Antioxidant activity.	Lins *et al.*, 2009
Levoglucose	*K. alvarezii*	Antibacterial activity against *Bacillus cereus*	Bhuyar *et al.*, 2020
Bioactive peptides and carbohydrates	*U. lactuca, Jania rubens, Pterocladia capillacea*	Dietary supplement of Nile tilapia	Ashour *et al.*, 2020

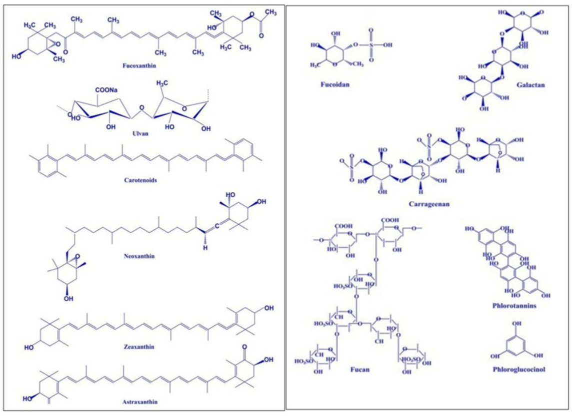

Fig. 1. Chemical structure of different bioactive compounds produced by seaweeds.

The research done to investigate the bioactive compounds produced by different seaweed species is summarized in Table 2.

Extraction methods of bioactive compounds from seaweed

The major bioactive compounds in seaweeds include polyphenols, carotenoids, vitamins, phycobilins, phycocyanins, and polysaccharides (Kadam and Prabhasankar, 2010). However, the other bioactive compounds such as sulfated and branched polysaccharides are bound to proteins and ions (calcium and potassium) (Doi and Kosugi, 2004). Hence, to extract the bioactive molecules from the seaweeds, it is essential to breakdown the compounds (Kadam *et al.*, 2015). Among the several methods available to breakdown the compounds to obtain bioactive molecules, supercritical fluid extraction is widely adopted (Herrero *et al.*, 2015). Under pressurized hot water extraction, liquid water was used as an extractant at a temperature above the atmospheric boiling point of water (100 °C, 0.1 MPa), but below the critical point of water (374 °C, 22.1 MPa) (Plaza and Turner, 2015). In the enzymatic extraction, cellulase and xylinase were used to isolate the bioactive compounds (Joubert and Fleurence, 2008). Furthermore, for extracting proteins from the seaweed *Porphyra* sp., in addition to the pretreatment with the enzyme protease, the wall-digesting enzyme mixture consisting of abalone and macirazyme R-10 was applied. Finally, the extraction was carried out in phosphate buffer (pH 7.5) and 0.1N NaOH (Amano and Noda, 1990).

The two-phase extraction method consists of a mixture of polyethylene glycol (PEG-1550) and potassium carbonate (phase1system), followed by extraction with bromoperoxidase (phase 2 system). Subsequent purification is carried out by chromatography and adopted for the seaweed species, L. *digitata* and L. *saccharina* (Jordan and Vilter, 1991). In addition, pulse electric field treatment (PEF) is applied tothe concentrated algal suspension of *Auxenochlorella protothecoides* that has been treated with square pulses of 1µs duration (Goettel *et al.*, 2013). The extraction method, extraction conditions, and the compound extracted are summarized in Table 3.

Table 3. Summary of literatures collected on the methods and conditions followed to extract bioactive compounds by various researchers.

Extraction method	Algal species	Extraction condition	Extracted compounds	Reference
Pulsed Electric Field Extraction (PFE)	*Ulva* sp.	Pulsed electric field of 124±12Vmm^{-1}, pulse duration : 50µs, pulse number: 50 and frequency 3Hz	Bio refinery feedstock	(Levhov *et al.*, 2020)
Supercritical fluid extraction	*Scenedesmus* sp.	-	Lutein, neoxanthin, zeaxanthin, astraxanthin, and β-carotein, using CO_2 at 30MPa and 60°C with 10% ethanol as cosolvent	Klejdus *et al.*, 2014; Herrero *et al.*, 2015
Microwave-hydrothermal extraction	*U. pinnatifida*	-	Lipids and polysachharides (fucoidan) Microwave heating at 140°C with short irradiation time of 1 minute	Quitain *et al.*, 2001

Extraction method	Algal species	Extraction condition	Extracted compounds	Reference
Ultrasound assisted extraction	*A. nodosum*	Extraction time: 25 minutes,Acid HCl : 0.03M Ultrasonic amplitude: 114µm	Total phenolics, fucose and uronic acid	Kadam *et al.*, 2015
Ultrasound assisted extraction	*L. hyperborea*	Ultrasonic power 60%, HCl 0.1M at 70°C for 2.5 hours	Laminarin	Kadam *et al.*, 2015
Ultrasound and enzyme assisted extraction	*S.muticum, Osmundea pinnatifida,* and *Codium tomentosum.*	Ultrasound extraction (sonication for 10 minutes and pause for 2 minutes) at 50°C Enzymes (alcalase, flavourzyme, cellulose, viscozyme L) at 50°C for 24 hours. Bioactive compound yield was higher in enzyme assisted extraction	Phenolic compounds	Rodrigues *et al.*, 2015
Enzyme assisted extraction	*S. boveanum, S.angustifolium, Feldmannia irregularis*	Multi-enzyme complex Viscozyme (containing arabinose, cellulose, β-glucanase, hemicellulose, xylanase) and endopeptidase alcalase Enzyme concentration : 0.1%,inactivation by heating 100°C for 10 minutes	Phenolic-rich and protein-rich fraction	Habeebullah *et al.*, 2020
Chemical extraction	*Hypnea musciformis, H. valentiae, Jania rubens*	Extraction with methanol at 50 to 60°C for 3hours Concentrating filtrate at 50°C and partitioned with Dichloro methane and Ethyl Acetate in vacuum	Phenolic compounds	Chakraborthy *et al.*, 2015
Solvent extraction	*Grateloupia lancifolia*	Extraction with diethyl ether and methanol at ambient temperature, evaporated the filtrates to absolute dryness under vacuum at 40°C	Phenolic compounds	Nguyen and Kim 2012
Solvent extraction	*Euchema* sp. *Kappaphycus*sp., *G. edulis* and *Acanthophora spicifera*	Extraction with methanol at 29±2°C for 24 hours under dark Fractionation by solvents such as petroleum ether followed by ethyl acetate, dichloromethane and n -butanol	Phenolic compounds	Ganesan *et al.*, 2008
Solvent extraction	*G. edulis, G. verrcosa, Acanthospora spicifera, Ulva facita, U.lacta, K. spicifera, S. ilicifolium, S. wightii, Padina tetramatica and P. gymonospora*	Extraction with solvents such as methanol, isopropanol, acetone, chloroform, diethyl ether (1:5w/v) using soxhlet apparatus for 24h and evaporation in vacuum	Phenolic compounds	Thirunavukkarasu *et al.*, 2013
Enzyme assisted extraction	*Kappaphycus* sp., *Gelidium* sp., *Sargassum* sp., *Laminaria* sp., *Ulva* sp.	Saccharification and fermentation at 2% (w/v) pretreated algal biomass, 6%(v/v) enzymes and yeast at 55°C for 18h	Bioethanol	Ramachandra and Deepthi 2020

Proteins from seaweeds

The species, location, growing conditions, and harvest seasons are crucial factors determining the chemical composition of the seaweeds (Kadam *et al.*, 2015). However, the yield of protein from seaweeds is higher (2.5-7.5t/ha/year) compared to the terrestrial crops (Gouveira *et al.*, 2008). The protein content of green and red seaweeds (10-47% Dry weight) is higher in comparison to brown seaweeds (3-15% DW) (Wijesekara and Kim, 2015). In addition, lectin and phycobiliproteins are important bioactive proteins, and angiotensin-converting enzyme (ACE1) is found in brown seaweeds (Fitzgerald *et al.*, 2011). Furthermore, seaweeds are vital sources of essential amino acids, such as histidine, leucine, isoleucine, and valine (Freitas *et al.*, 2015). In addition, agar is used as a gelling agent and is produced from seaweeds belonging to *Gracilaria* and *Gelidium* genera (Cregut and Rondags, 2013).

The studies on the structure and properties of seaweed proteins are not yet well-established (Admassu *et al.*, 2017). The protein isolation method is time-consuming and costly (Wijffels and Barbosa, 2010) because it is rather challenging to extract proteins from seaweed as they are available as intracellular compounds (Harnedy and FitzGerald, 2011; Fleurence *et al.*, 2012) and are highly cohesive with polysaccharides, thereby providing a poor yield.

Therefore, proteins are isolated by the modified version of the protein shift method (Vilg and Undeland, 2017). The protein yield from *Entamorpha* sp., was 6% (Kandasamy *et al.*, 2012), that from *Kappaphycus* was 8% (Kumar *et al.*, 2014), *S. latissimi* was 16% (Vilg and Undeland, 2017), and *U. latuca* and *Porphyraumbilicalis* 6.4% and 22.6%, respectively (Harrysson *et al.*, 2018). The precipitation of seaweed protein was improved by freeze/thaw cycles after adjusting the pH to 2.0 for a high yield (Abdollahi *et al.*, 2019). Recently, the protein was extracted from *Chondrus crispus*, *A. nodosum*, *S. latissima*,and *U. lactuca* (Wijers *et al.*, 2020).

Nanomaterials from seaweed

Nanomaterials are ultra-small-sized particles with unique physical and chemical characteristics (Tian *et al.*, 2013) with wide applicability in various fields, such as medicine, environment, and industries (food, cosmetics). These are mainly prepared from various chemicals, and hence, it is found that these chemical-based nanoparticles pose serious environmental hazards. In order to overcome this issue, researchers are focusing on the synthesis of plant-based nanoparticles in an ecofriendly manner (Roy *et al.*, 2019). Interestingly, nanoparticles have been synthesized from various plant species, including garlic and celery (Priyanka and Sheela, 2017), onion (Khalilzadadeh and Borzoo, 2016), and *Mussaenda frondosa* L. (Jayappa *et al.*, 2020). Furthermore, culture filtrates of *Lactobacillus* sp. have been used to synthesize nanoparticles (Matei *et al.*, 2020). However, currently, synthesizing the nanoparticles from seaweeds is under intensive focus because these plants are renewable and available in abundance (Roy *et al.*, 2019). Also, metallic nanoparticles are synthesized from seaweeds. Among these, silver nanoparticles (AgNPs) are synthesized from extracts of both fresh and dry seaweeds of *Codium capitatum*. Strikingly, fresh seaweeds yielded more AgNPs than dry weeds (Kannan *et al.*, 2013). It was reported that green biosynthesis of iron oxide nanoparticles (Fe_3O_4-NPs) is achieved by reduction of ferric chloride solution with brown seaweed *S. modicum* (Mahdavi *et al.*, 2013). The brown marine macroalgal species *P. gymnospora* extract was used to synthesize gold nanoparticles (AuNPs) by reduction of an aqueous solution of $AuCl_4$-ions in an ecofriendly manner (Singh *et al.*, 2013). Moreover, AuNPs synthesized with the extract of the seaweed *Galaxaura elongate* in the normal atmospheric condition werefound to have antibacterial activity against *Klebsiella pneomoniae*, *Escherichia coli*, *Staphylococcus aureus*,and *Pseudomonas aeruginosa* (Abdel-Raouf *et al.*, 2017`). In addition, the AuNPs synthesized from red seaweed *G. verrucosa*were compatible with normal human embryonic kidney (HEK293) cells (Chellamuthu *et al.*, 2019).

Further, AgNPs with antibacterial activity were synthesized by reducing the aqueous solution of silver nitrate ($AgNO_3$) with powder and extracts of *P. pavonia* (Bhuyar *et al.*, 2020). On the other hand, the red seaweed *G. birdiae was* found to be a source of production of spherical-shaped AgNPs with hydrodynamic diameters between 20.3 and 94.9nm with negative zeta potential and bactericidal activity against Gram-negative bacterial species (de Aragao *et al.*, 2019). Recently, $Mg(OH)_2$ non-material with antibacterial activity against *Mycobacterium tuberculosis* has been synthesized from *Turbinaria ornate* (Govindaraju *et al.*, 2020).

Biochar from seaweed

The value-added product charcoal/biochar obtained from agricultural, forestry, and industrial residues, poultry manure, urban waste, and sewage sludge is utilized to improve the soil health (Lehmann and Joseph, 2009). Biochar is the solid carbon-rich product obtained by pyrolysis of biomass at high temperatures with deliberate exclusion of oxygen (Alhashimi and Aktas, 2017). The degradable biomass is converted into recalcitrant biochar before adding into the soil sequesters carbon into the land. The application of biochar for environmental benefit is emerging steadily. Some studies have been conducted to demonstrate the importance of biochar for various applications, such as improving soil health, minimizing *in-vitro* rumen gas(CH_4) emission, suppressing soil-based emissions of CH_4 and N_2O, and retention and slow release of nutrients. Although its structure is uncertain, biochar has recently gained increasing attention (Kim *et al.*, 2012). The biochar is more similar in characteristics to that produced from poultry litter than those derived from the lignocellulosic feedstock, indicating that like poultry litter biochar, macroalgal biochar has properties that provide direct nutrient benefits to soils and crop productivity, rendering it beneficial for acidic soils (Bird *et al.*, 2012). The different feedstock including seaweed used for biochar production and the characteristics are furnished in Table 4.

Table 4. Feedstock other than seaweed used for biochar production and the characteristics.

Feedstock	Pyrolysis temperature	Characteristics	Reference
Miscanthus	400 - 600°C	High sorption efficiency of Cd, Pb, Zn	Janus *et al.*, 2015
Poultry litter	400 - 600°C	High ash, ammonium nitrogen and volatile fatty acid contents	Rombola *et al.*, 2015
Pecan shell	350 - 500°C	High Specific Surface Area(SSA) due to its intrinsic high density	Novk *et al.*, 2009
Oak (*Allocasuarina torulosa*)	300 - 900°C	pH 7.23 to 8.77 More element concentration	Zhang *et al.*, 2017
Pine(*Pinus radiata*)	300 - 900°C	pH 5.38 to 8.33 More element concentration	Zhang *et al.*, 2017
Sugarcane bagasse	300 - 600°C	pH 3.5 to 4.9 More element concentration	Zhang *et al.*, 2017; Zhang *et al.*, 2019
Peanut shell	300 to 900°C	pH 6.6 to 9.34	Zhang *et al.*, 2017
Pine needle	100 to 700°C	Surface area 0.65 to 490 m^2/g	Chen *et al.*, 2008
Cotton seed hulls	350 to 800°C	4.7 to 322 m^2/g	Uchmiya *et al.*, 2011
Oakwood	350 to 600°C	450 to 642 m^2/g	Nguyen *et al.*, 2011
Corn stover	350 to 600°C	293 to 527 m^2/g	Nguyen *et al.*, 2009
Broiler litter manure	350 to 700°C	59.5 to 94.2m^2/g	Uchimiya *et al.*, 2010
Soybean stock	300 to 700°C	144.14 to 250.23m^2/g	Kong *et al.*, 2011
Sewage sludge	400 to 600°C	CEC and EC decreases with pyrolysis temperature	Mendez *et al.*, 2013
Sewage sludge	600°C	pH 9.43 EC (1:2.5) µScm^{-1}, 25°C - 4200 CEC /cmolkg^{-1} -8.15	Paz-Ferreiro *et al.*, 2012
Sewage sludge	450°C	Had rich micropores, relatively stable functional groups in structure and rugged surface to contact well with soil	Song *et al.*, 2014
Municipal sewage sludge	900°C	pH 12.15, CEC/c mol.kg^{-1} - 24.7 ±7	Li *et al.*, 2018
Wood Biomass (*Gliricidia sepium (Jacq.*)	300°C 500°C	pH 6.71, EC 0.21 ds/m, CEC 439Cmol/kg pH 9.27, EC 0.54 ds/m, CEC 498Cmol/kg	Bandana *et al.*, 2017
Gracillaria sp.	450°C	pH 7.6±0.2 - 8.1±0.1	Roberts *et al.*, 2015
Eucheuma sp.	450°C	pH 8.1±0.1 - 8.6±0.1	Roberts *et al.*, 2015
Kappaphycus sp.	450°C	pH 8.2±0.2 - 9.6±0.1	Roberts *et al.*, 2015
Saccharina sp.	450°C	pH 11.0±0.3 -11.2±0.1	Roberts *et al.*, 2015
Sargassum sp.	450°C	pH 10.1±0.2 - 10.8±0.1	Roberts *et al.*, 2015
Undarina sp.	450°C	pH 9.9±0.1 --10.9±0.1	Roberts *et al.*, 2015
E. prolifera and corn straw	400°C	pH 9.36-9.47, higher water soluble N/P content, larger surface area, low Na content, and slower nutrient release rate	Suo *et al.*, 2021
A. nodosum	700°C	Surface area 19.815m^2/g	Katiyar *et al.*, 2021
S. crassifolium	500°C	pH 10.41, Total ash content 54.99%	Atugoda *et al.*, 2021

Feedstock	Pyrolysis temperature	Characteristics	Reference
S. duplicatum	700°C	Carbon content 34 wt%	Hung *et al.*, 2021
Agardhiella subulata	900°C	Uniform spherical shaped particles(approximately 30 nm)	Hung, 2020
Enteromorpha prolifera	300 - 700°C	Low C content (29.6-37.4%); High O (16.6-28.9%) and N (0.75-3.48%) ash content 33.5-63.5%	Zhao *et al.*, 2022
U. prolifera	300°C	Rough and porous structure	Govindaraju *et al.*, 2022

A recent study demonstrated that biochar with high exchangeable nutrient content and cation exchange capacity (CEC) could be produced from seaweed (Bird *et al.*, 2011; Bird *et al.*, 2012; Roberts *et al.*, 2015). Moreover, marine macroalgae, *S. fusiforme* (hijikia) and *S. japonica* (kelp), are utilized for the production of biochar (Poo *et al.*, 2018). The possibility of utilization of macroalgal species (seaweed) for the production of biochar has been investigated previously using eight algal species. It was observed that the biochar has characteristics similar to that obtained from poultry litter and lingocellulosic feedstock with high pH, nitrogen, and extractable inorganic nutrients, including phosphorus, calcium, potassium, and magnesium (Bird *et al.*, 2011). Furthermore, the biochar obtained from *E. clathrate* at 800°C was found to be a promising metal modified biochar catalyst for producing acid-free bio oils with more esters and sugars (Cao *et al.*, 2021).

However, the preparation and application of biochar from algal species are in the emerging stage. Different types of reactors are used to produce biochar from algal species. It has been reported that a spouted fluidized bed reactor was used to pyrolyze *Senedesmus* sp. at 480°C (Harman-Ware *et al.*, 2013), and nitrogen-rich biochar was obtained from *Chlamydomonas reinhardtii* biomass at 350°C (Torri *et al.*, 2011). Dual-bed slow pyrolysis is another method employed to convert the biomass of marine algal species (*Sargassum* sp.) to biochar at 400-800 °C (Taghavi *et al.*, 2018). Venice lagoon brown microalga *L. japonica* was used to produce biochar catalyzed by Ni/SBA-15 (Jung *et al.*, 2016). The biochar produced from macroalgal species (*Oedogonium* sp.) by slow pyrolysis enhanced the rehabilitation of a variety of soils of Coalmine-Ferro sol and sodic soil, which enhanced the growth of Kangaroo grass (*Themeda autralia*) (Roberts *et al.*, 2015).

Agricultural applications of seaweed

Presently, the seaweed extract is applied for crop growth due to its agricultural significance (Bouckhari *et al.*, 2020). Seaweeds have several growth-regulating hormones (indole acetic acid (IAA), indole-3-butyric acid (IBA), and cytokinins), trace elements (Mo, Fe, Cu, Ni, and Zn), vitamins, and aminoacids (Khan *et al.*, 2009). In addition, seaweed extract is one of the major non-microbial biostimulants (Rouphael and Colla, 2020). This phenomenon was further confirmed by other studies, wherein marine algae were shown to harbor growth-promoting substances (cytokinins and giberellins), trace elements, vitamins, aminoacids, and micronutrients and enhance crop growth (Nabti, 2019). When seaweeds are used as fertilizer for crops, the rate of photosynthesis, chlorophyll a and b content and activities of protective enzymes, such as superoxide dismutase, ascorbate peroxidase, and catalase are improved markedly. Furthermore, the soil microbial population was enhanced with seaweed application (Wangetal., 2017). For crops growing under environmental stress conditions, the growth and yield have been improved by the application of seaweed extract. It was observed that the growth and yield are improved when the crops are grown under drought conditions in the presence of seaweed extracts (*Sargassum* sp. and *Ulva* sp.). The seaweed extract influences the crop by activating the antioxidative enzymes, such as catalase, peroxidase, and ascorbic acid, controlling the oxidative damage caused by drought, and indirectly by providing the micro- and macronutrients essential for crop growth (Kasim *et al.*, 2015, Additionally, seaweed extract is used as a soil conditioner or foliar spray to stimulate crop growth Chernane *et al.*, 2015). The effect of seaweed extract application on crop growth is illustrated in Fig 2.

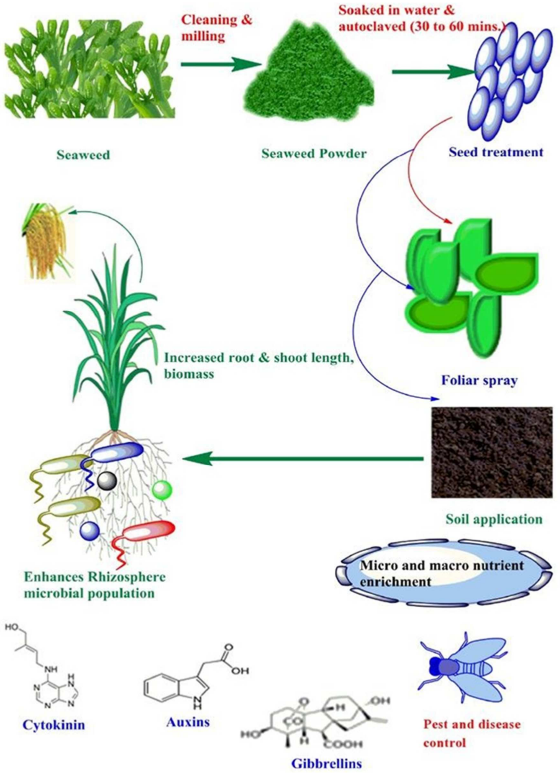

Fig. 2. Illustration showing effect of seaweed extract on crop growth.

The different sea weed species utilized as crop growth stimulant and the mode of application is given in Table 5.

Combined effect of seaweed extract with other amendments on crop growth

When seaweed extract is applied with other amendments, the cumulative effect on crop growth is improved. Biochar (2%) along with seaweed extract (2% and 4%) has increased the growth and yield of wheat (*Triticum aestivum* L.). Also, the micro- and macronutrient content in the roots, leaves, and grain has been increased (Salim, 2016). The yield and nutritional quality of *A. esculentus* was found to be increased when seaweed liquid extract (0.4%) and humic acid formulation (8%) were applied combined to the crops (Prakash *et al.*, 2018). However, the seaweed extract (liquid and paste) enhanced the root and shoot growth of cluster bean (*Cyamopsis tetragonoloba*) when applied along with vermiwash (Chithra *et al.*, 2016).

Table 5. Effect of seaweed extract on crop growth and yield.

Seaweed species	Mode of application	Outcome	Reference
A. nodosum	Soil Application	Improved fruit quality of watermelons, grapes, apples and olives	Frioni *et al.*, 2018
		Ripening rate of grapes increased	Arioli *et al.*, 2021
K.alvarazii	Foliar spray (0,2.5, 5.0,7.5,10,15% v/v)	Soybean (*Glycine max L.*)	Rathore *et al.*, 2009
S. wightii	20%	Percentage of seed germination, growth and yield of *Triticum aestivum* var. Pusa Gold	Kumar and Sahoo 2011
S. harneri	0, 10, 30, 60 and 90kg/ m²	Tomato yield increase by 4.6 to 6.9% 60 to 90kg h/m2 there was significant increase in the hardness of tomato by 10.2 and 19.8% respectively	Yao *et al.*, 2020
S. tenerrimum	10%	Improved yield in tomato, resistance to Macrophomina phaseolina by modulating phytohormones and antioxidative enzymes	Khedia *et al.*, 2020
K.alvarezii *Gracilaria spp.*	0, 2.5, 5, 7.5, 10 and 15%v/v	Maize (*Zea mays*) Grain yield 30q/ha Fodder yield 86.77q/ha	Pal *et al.*, 2015
S. wightii,. *K. alvarezii*	75% (v/v)	Chilli (*Capsicum annum*) - enhanced the growth and yield parameters	Jayasinghe *et al.*, 2016
Sargassum sp.1 *Sargassum* sp.2 *S. polycistum,* *Turbinaria ornate* *T. murayana* *Hydroclarthus* sp.	Not mentioned	Enhanced growth and increased yield of rice	Sunarpi *et al.*, 2010
G. edulis, *E. intestinalis,* *Chaetomorpha linum*	40 to 60%	Better seed germination in *Abelmoschus esculentus* and *Solanum lycopersicum*	Arun *et al.*, 2014
Kappaphycus sp. *Gracilaria* sp.	Foliar spray 15%	Increased grain yield and improved nutrition content	Pramanik *et al.*, 2013

Seaweed species	Mode of application	Outcome	Reference
K. alvarezii	Foliar spray 2.5%	Fruit yield of Okra(*Abelmoschus esculentus* L.) increased by20.44%	Zodape *et al.*, 2008
A. nodosum	Foliar spray	Pepper (cv. California wonder) - fruit yield, length and diameter increased	Eris *et al.*, 1995
A. nodosum	Foliar spray	Broccoli - Quality of fruit was improved. Increased total phenolic, total flavanoide and total isothiocyanates content.	Lola-Luz *et al.*, 2014
Rosenvigea intricata	Foliar spray 20%	London bean (*Cyamopsis tetragonoloba*) The seed germination, growth and yield parameters such as shoot length, root length, number of lateral roots, number of leaves, number of vegetables, length of vegetables, weight of vegetables, photosynthetic pigment concentration such as chlorophyll 'a', chlorophyll 'b', total chlorophyll and carotenoids was found to be maximum	Thirumaran *et al.*, 2009
K.alvarezii	Seed treatment 2.5 to 5.0%	In paddy (*Oryza sativa*) increased germination percentage, shoot length and seedling vigor index	Layek *et al.*, 2017
G. edulis	Foliar spray ≥5.0%	increased plant height, dry matter production, chlorophyll index, yield and micronutrient content	
Stoechospermum marginatum	Foliar spray 1.5%	shoot length, root length, fresh weight, dry weight, leaf area increase in *Solanum melongena*	Ramya *et al.*, 2015
A. nodosum	Foliar spray 0.01%	The seed germination, shoot length, root length, fresh weight and dry weight were found to be maximum	Verma *et al.*, 2017, Shukla *et al.*, 2019
	0.05%	free radical scavenging and alpha glucosidase inhibition activityincreased	
S. tenerrimum	0.6% Seed treatment, soil treatment and foliar spray	Tomato(*Solanum lycopersicum)* increased plant growth and yield	Sasikala *et al.*, 2016
S.wightii, Turbinaria ornata, C. racemosa	Foliar spray 10%	Tulsi(*Ocimum sanctum*) - Increased plant growth, protein and chlorophyll contents	Uthirapandi *et al.*, 2018
K.alvarezii	Soil treatment 2.5%(v/v)	Maize (*Zea mays*) Enhanced root growth and yield increased	Kumar *et al.*, 2020
A. nodosum *Sargassum* sp.	Foliar spray 0.5% (v/v)	Tomato (*Lycopersicon esculentum*) Increased flower bud, flower and fruit number	Dookie *et al.*, 2020
Durvillaea potatorum *A. nodosum*	Soil treatment Fortified with calcium 1% (w/v)	Tomato (*L. esculentum* Var. *Grosse Lisse*) Yield increased, soil microbial activity enhanced	Hussain *et al.*, 2021
Cultured kelp	Foliar spray 3L/ha	Sugarcane (*Saccharum officinarum)* Increased cane yield and sucrose content	Chen *et al.*, 2021
Ecklonia maxima	Foliar spray 1%	Okra (*Abelmoschus esculentus)* Stimulated seed germination	Mackaya *et al.*, 2021
E. maxima	Foliar spray 8 µmol/L	Spinach (*Spinacia oleracea* L.) Increased yield and enhanced quality	La Bella *et al.*, 2021
U. lactuca *Jania rubens* *Pterocladiella capillacea*	Foliar spray 10%	Arugula (*Eruca vesicaria* L.)	Hassan *et al.*, 2021
E. maxima *A. nodosum*	Rosa sp.	10% Improved rooting rate	Traversari *et al.*, 2022
U. latusa *S. latissima*	*Arabidopsis thaliana*	Resistant against white rust (*Albugo* sp.)	Jensen and Jorgensen, 2022
A. nodosum	Sweet pepper	Root treatment and foliar spray 0.5% Improved germination%, shoot growth, production of biochemical constituents namely chlorophyll, reducing sugars, amino acids, and phenols	Rajendran *et al.*, 2022

The extracts of the seaweeds (*Macrocystis pyrifera*, *Bryothamnion triquetrum*, *Ascophyllum nodosum*, *Grammato phora* sp., and *Macrocystis integrifolia*) improved the fruit quality when the antioxidant content of cucumber (*Cucumis sativus*) was applied in combination with compost (Valencia *et al.*, 2018). Recently, it has been demonstrated that, when seaweed extract was applied along with two PGPR namely, *Pseudomonas fluorescence* and *Bacillus licheniformis,* the crop productivity and mineral nutrition of onion (*Allium cepa*) was enhanced (Gupta *et al.*, 2021). Likewise, there was an increase in flavonoids and phenolics content in lettuce (*L. sativa*), when extract of *A. nodosum* (3g/L) was applied along with Arbuscular mycorrhiza (*Glomus mosseae*) (Rasouli *et al.*, 2022). Furthermore, the study conducted by Arab *et al.* (2022) revealed that extract of *A. nodosum* (0.3%) and Ellagic acid (50 mg/L) increased the protein content and yield of soybean. In addition, seaweed extract application along with vermicomposting leachate and smoke-water alleviated drought stress in cowpea (*Vigna unguiculata* L. *Walp*) (Voko *et al.*, 2022), resistant to pest (*Magnaporthe oryzae*) in rice due to the secretion of defense - related enzymes namely, phenylalanine ammonia lyase, chitinase, peroxidase, polyphenol oxidase and phenolics (Sahana *et al.*, 2022). Application of 0.5mL/ *L* 'Primo' (*Ascophylum nodosum* seaweed extract + amino acid and) + 0.01% 'Tween 20′) improved vegetative growth and yield and quality of citrus fruit (Khan *et al.*, 2022).

Conclusion and future scope

Seaweeds are widely distributed, and the distribution is affected by various factors. The important bioactive compounds of seaweeds such as fucoidan, ulvan, carotenioids, and fucoxanthin are commercially used in various fields. Further improvement in the methods and environmental conditions is required for the extraction of bioactive compounds from seaweeds to increase the product yield. Additional studies are needed to explore the distribution of seaweeds and identify the species to produce value-added products. Limited studies are available to evaluate the importance of seaweed extract when combined with other amendments, thereby necessitating further study. If these issues are addressed, seaweed is the better alternative to chemical fertilizer in the agricultural field. Hence, it is concluded that the naturally available resource, such as seaweed, could harness the benefits.

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