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Pharmacological potential of seaweed derived bioactive compounds: Applications for next generation crop improvement

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Abstract

The agriculture sector is facing several major challenges, including increasing population pressure, climate change and excessive dependence on chemical fertilizers; all of which threaten long-term sustainability. At the same time, increasing population, industrial growth and urbanization have intensified the need to explore marine resources. Among the diverse living resources of the oceans, seaweeds represent a valuable group due to their richness in bioactive compounds and their extensive agricultural applications. Extensive research has documented the positive effects of seaweed extracts on crops, including enhanced seed germination, improved root and shoot development, greater seedling vigour, increased flowering and fruit set, higher marketable yield and improved resistance to drought, pest and disease. Seaweeds contain a wide array of phytochemicals, terpenoids, alkaloids, phenolics, flavonoids, sterols, tannins, carotenoids, amino acids, vitamins and sulfated polysaccharides, agar, alginate, carrageenan with antioxidant, antimicrobial, antiviral, anti-inflammatory and antifungal properties. Significantly, they are rich in natural plant growth regulators such as cytokinins, auxins, gibberellins, brassinosteroids, betaines and abscisic acid, which regulate cell division, elongation, photosynthesis, stress tolerance and overall physiological performance. This review examines taxonomy, extraction techniques and the effects of seaweed extracts on plant growth, soil fertility, biochemical enrichment, metabolic regulation and stress adaptation. It also highlights their phytochemical and phytomedicinal properties, emphasizing the functional role of bioactive compounds and natural plant growth regulators in enhancing plant defense responses and boosting crop productivity. The overall impact of this review highlights the potential of seaweed-based biostimulants as powerful, natural and sustainable alternatives to chemical fertilizers. Their integration into agricultural practices offers a promising pathway toward enhanced crop productivity, reduced environmental degradation and the development of resilient farming systems aligned with global sustainability goals.

1. Introduction

India is a predominantly agrarian country where agriculture serves as the main source of livelihood for approximately 70% of the population. In modern times, organic agriculture has emerged as an eco-friendly production system capable of generating high-quality produce without harmful environmental effects. To meet the increasing demand for organic nutrient sources, several commercially viable alternatives have been explored. Among these, seaweeds from natural resources have gained significant attention from both the scientific community and industry. The uses of seaweed are multifaceted, spanning medicinal, cosmetic, energy, fertilizer and industrial applications such as agar and alginate production. Their beneficial effects are primarily attributed to their high levels of minerals, vitamins, phytohormones, phenols, polysaccharides,

sterols and other bioactive compounds. These constituents possess antioxidant, osmoprotective, anti-inflammatory, anticancer, antimicrobial, antifungal and anti diabetic properties. Additionally, seaweed-based products enhance soil mineral nutrition, plant nutrient uptake, soil structure and aeration (Tejasree *et al.*, 2024). They also improve tolerance to abiotic and biotic stresses (Kumar *et al.*, 2024), stimulate root growth development, break seed dormancy, increase flowering, enhance fruit quality, yield and ultimately contributing to higher crop productivity. According to the Central Marine Fisheries Research Institute (ICAR-CMFRI), India produced 72,385 tonnes (wet weight) of seaweed in 2023, primarily from the cultivated species *Kappaphycus alvarezii* and *Gracilaria edulis*, which are widely used for carrageenan and agar extraction. To strengthen the sector, the Government of India launched the Pradhan Mantri Matsya Sampada Yojana (PMMSY) in June 2020, with a total investment of Rs.20,050 crore, identifying seaweed cultivation as a priority component. The production of biostimulants derived from seaweed is significantly more environmentally friendly compared to synthetic fertilizers (Singh *et al.*, 2018). Seaweed extracts can be applied through foliar spraying, fertigation or soil amendment, enhancing crop development, growth and product quality, as demonstrated by Van Oosten *et al.* (2017). When applied alone or in combination with micronutrients,

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these extracts can substantially reduce ecological risks, negative impacts and the indiscriminate use of chemical inputs. This review aims to highlight seaweed classification, extraction methods, the effects of seaweed application on crop growth and productivity, soil health, influence on biotic and abiotic stress tolerance and the phytochemicals present in different seaweed extracts. It also delineates strategies for using these extracts to achieve the most sustainable outcomes in agriculture.

2. Seaweed classification

Seaweeds can be classified into three broad groups based on their photosynthetic pigments, *viz.*, Phaeophyceae (brown algae), Rhodophyceae (red algae) and Chlorophyceae (green algae). Brown seaweeds are generally large in size and are rich in chlorophyll *a* and *c*, as well as fucoxanthin, giving them a yellow to deep brown colour (Dhargalkar and Pereira, 2005). Red seaweeds are usually smaller; although they are commonly red, some species may appear pink or even brownish-red. They are rich in chlorophyll *a*, phycobilins and carotenoids and serve as the primary raw material for extracting agar and carrageenan. Green seaweeds are also small in size and similar to red seaweeds; contain chlorophyll *a* and *b*, along with carotenoids. They typically grow in cold waters and thrive best at temperatures up to 20°C. These species are suitable for alginate production and are rarely used as food.

2.1 Distribution of seaweeds in Tamil Nadu and India

In India, seaweeds are found most abundantly along the southeastern and northwestern coastal regions. Nearly 7,500 km of India's coastline consists of rocky areas in the littoral and sub-littoral zones, providing ideal conditions for seaweed growth. More than 24,000 hectares of the coastal region have been identified as suitable for seaweed farming, with an estimated annual production potential of up to 10 million tonnes (wet weight), if large-scale cultivation is implemented. Major production centers include Tamil Nadu, Gujarat, Maharashtra and Lakshadweep, where pilot commercial-scale farming particularly in Lakshadweep has shown encouraging results (Ghorela *et al.*, 2025). Seaweeds grow along the coasts of Gujarat, Lakshadweep, the Andaman and Nicobar Islands, Goa, Karnataka, Andhra Pradesh and Tamil Nadu. The islands of the Gulf of Mannar harbor abundant species of *Acanthophora*, *Sargassum*, *Hypnea*, *Turbinaria*, *Gelidiella* and various *Ulva* species (Ganesan *et al.*, 2019). All three major groups of seaweeds, *viz.*, brown, green and red algae are richly diverse in the Gulf of Mannar, located in the southern region of Tamil Nadu.

2.2 Seaweeds composition

Several bioactive compounds are present in seaweeds. Compounds found in algae-derived extracts include zeatin, auxins, indole-3-acetic acid (IAA), gibberellins, kinetin, jasmonates, strigolactones, salicylic acid, brassinosteroids, 6-benzylaminopurine, cytokinins, ethylene, and abscisic acid, all of which are plant growth regulators. Seaweeds also contain macro and micronutrients such as calcium, phosphorus, magnesium, potassium, nitrogen and sulfur. Polyamines and betaines are also present (Zhang and Ervin, 2008). Seaweeds additionally contain alginates, osmoprotectants, humic acid, castasterone, polysaccharides, carrageenans and laminarin. Moreover, seaweeds contain a wide range of organic compounds, including fiber, polyunsaturated fatty acids, proteins, cellulose, hemicellulose, lignin (Mirparsa *et al.*, 2016) and halogenated constituents such as bromine, vitamins, and iodine. Researchers have also found that green, brown

and red algae synthesize compounds with anthelmintic, cytostatic, antiviral, antibacterial and antifungal properties (Newman *et al.*, 2003). Seaweeds and their derivatives are also a good source of biochemicals, including vitamins A, B, B2, and C, mineral elements and chelated micro-minerals such as selenium, chromium, nickel and arsenic, polyunsaturated fatty acids; bioactive metabolites and amino acids. The use of seaweed-derived substances in the development of new natural therapeutics is a major goal of marine pharmacology, a rapidly growing field that has been evolving over the past several decades.

3. Seaweed extraction methods

3.1 Preparation of seaweed liquid fertilizer

3.1.1 Seaweed liquid fertilizer preparation using water

The seaweeds were washed with water and chopped into smaller pieces and were boiled with an equal quantity of water for one h and filtered, resulting in a 100% concentrated extract. The solution was heated to 60°C for 45 min on a magnetic stirrer with a hot plate to ensure thorough mixing of the solute. After 1 h, it was filtered at room temperature (15-20°C), then solution was stored in separate plastic bottles until used (Eswaran *et al.*, 2005).

3.1.2 Preparation of seaweed liquid fertilizer using ethanol

Powdered seaweed (100 g) was soaked in 100 ml of alcohol and each organic solvent separately (ethanol, hexane, ethyl acetate, chloroform and diethyl ether) for over-night with intermittent stirring and it was filtered. The filtrate was assumed to have a 100% concentration

3.1.3 Preparation of seaweed liquid fertilizer

The seaweeds were dried in the shade for 10 days, followed by oven drying at 60°C for 2 days. After drying, the seaweeds were powdered using a wiley mill. A total of 500 g of seaweed powder was dissolved in 1000 ml of water and left to stand for 1 h at room temperature. The extracts were then filtered using filter paper and stored at 4°C for later use (Anisimov *et al.*, 2013).

3.2 Different extraction methods

3.2.1 Acidic extraction

Acidic extraction is a common technique for isolating bioactive compounds, such as carrageenans and agar from seaweed. This method involves treating seaweed with dilute acids like hydrochloric acid or sulfuric acid under controlled conditions to break down the cell walls and release target compounds. Acidic conditions hydrolyse polysaccharides, facilitating the extraction of sulphated galactans while maintaining their bioactivity. Key parameters such as acid concentration, temperature and extraction time influences the yield and quality of the extracts. Acidic extraction is efficient and widely used in the production of hydrocolloids but requires careful optimization to prevent degradation of sensitive compounds (Animish *et al.*, 2024).

3.2.2 Alkaline extraction

Alkaline extraction is a widely used method for isolating bioactive compounds, particularly polysaccharides like alginates, from seaweed. The process involves treating seaweed biomass with an alkaline solution, commonly NaOH or KOH under controlled

conditions of temperature and time. Alkaline treatment breaks down the cell wall matrix, releasing intracellular components and solubilizing targeted compounds. The efficiency of extraction depends on factors such as alkali concentration, extraction temperature and duration. This method is scalable and widely applied in both research and industry for seaweed byproducts (Marcin *et al.*, 2024).

3.2.3 Solid-liquid extraction (SLE)

Solid-liquid extraction (SLE) is a widely used technique for isolating bioactive compounds from seaweeds, involving the use of solvents to extract desired components from the seaweed matrix. The process typically begins with drying and pulverizing the seaweed to increase surface area, followed by mixing with a suitable polar solvents like water, methanol or ethanol for hydrophilic compounds and non-polar solvents like hexane or ethyl acetate for lipophilic compounds. The extraction efficiency depends on factors such as solvent type, temperature, solid-to-liquid ratio and extraction duration. After extraction, the liquid phase is separated by filtration or centrifugation and the solvent may be removed or concentrated using evaporation techniques. SLE is simple, cost-effective and scalable, making it ideal for extracting compounds like polysaccharides, phenolics and pigments (Magnusson *et al.*, 2017).

3.2.4 Soxhlet extraction

Soxhlet extraction is a traditional and widely used method for extracting bioactive compounds from seaweed, particularly for lipophilic substances like fatty acids, pigments and sterols. This technique involves continuous solvent reflux through a thimble containing the seaweed sample, allowing the solvent to repeatedly extract compounds, which are then condensed and collected. It requires longer extraction times, large solvent volumes and high extraction efficiency. While it is effective in isolating a broad range of compounds, the method may not be as environmentally friendly or energy-efficient as newer extraction techniques, which is often used for large-scale extractions of specific target compounds (Crespo *et al.*, 2005).

3.2.5 Supercritical fluid extraction (SFE)

Supercritical fluid extraction (SFE) is an advanced technique for extracting bioactive compounds from seaweed, utilizing supercritical fluids like carbon dioxide (CO₂) as solvents. At critical temperature and pressure, carbon dioxide exhibits properties of both liquid and gas, allowing efficient penetration into the seaweed matrix and selective extraction of compounds such as lipids, carotenoids and sterols. The process is environmentally friendly, as carbon dioxide is non-toxic, reusable and eliminates the need for organic solvents. Parameters such as temperature, pressure and co-solvent addition (*e.g.*, ethanol) can be optimized to enhance yield and selectivity. SFE offers high efficiency, minimal thermal degradation and cleaner extracts compared to conventional methods, making it ideal for high-value bioactive recovery from seaweed (Crespo *et al.*, 2005).

3.2.6 Pressurized liquid extraction (PLE)

Pressurized liquid extraction (PLE), also known as accelerated solvent extraction, is an efficient method for extracting bioactive compounds from seaweed using solvents at elevated temperatures (50-200°C) and pressures (10-15 MPa). These conditions enhance solvent penetration and solubility, improving extraction efficiency. PLE is particularly effective for recovering compounds like polyphenols,

pigments and polysaccharides. Solvent choice (*e.g.*, water, ethanol or their mixtures) and operational parameters are critical for optimizing yields and preserving bioactivity. This method is eco-friendly and scalable, offering advantages like reduced degradation of thermolabile compounds and cleaner extracts compared to conventional techniques (Perez-Vazquez *et al.*, 2023).

3.2.7 Ultrasound assisted extraction (UAE)

Ultrasound - assisted extraction (UAE) is a green and efficient technique for isolating bioactive compounds from seaweed, leveraging ultrasound waves to enhance solvent penetration and disrupt cell walls. The cavitation effect generated by ultrasound creates microbubbles that collapse, improving mass transfer and releasing intracellular components like polyphenols, pigments and polysaccharides. UAE operates at mild temperatures, preserving thermolabile compounds and reduces extraction time and solvent use compared to conventional methods. Key parameters, such as ultrasound frequency, power, extraction time and solvent type, must be optimized for maximum yield. UAE is cost-effective, scalable and environmentally friendly, making it a promising method for seaweed extraction (Shekhar *et al.*, 2023).

3.2.8 Microwave-assisted extraction (MAE)

Microwave-assisted extraction (MAE) is an advanced technique for extracting bioactive compounds from seaweed, utilizing microwave energy to heat the solvent and disrupt cell walls, thereby enhancing the release of intracellular components. The rapid heating and localized high temperatures improve mass transfer, resulting in shorter extraction times and reduced solvent consumption. MAE is particularly effective for recovering compounds like polysaccharides, phenolics and pigments. Operating conditions, including microwave power, exposure time and solvent type, can be optimized to maximize yield and preserve bioactivity. This method is energy-efficient, scalable and environmentally friendly, making it a valuable tool for seaweed extraction (Rodriguez-Jasso *et al.*, 2011).

3.2.9 Enzyme-assisted extraction (EAE)

Enzyme-assisted extraction (EAE) is an eco-friendly technique for recovering bioactive compounds from seaweed, using specific enzymes such as cellulase, alginate lyase or protease to degrade cell walls and release intracellular components. This method operates under mild conditions, preserving heat-sensitive compounds while enhancing the yield of polysaccharides, phenolics and proteins. EAE reduces the need for harsh chemicals and extensive processing, making it sustainable and cost-effective. The efficiency of extraction depends on factors like enzyme type, concentration, pH, temperature and reaction time, which can be optimized for specific compounds. EAE is a promising approach for sustainable utilization of seaweed resources (Rhein-Knudsen *et al.*, 2015).

3.2.10 Liquefied gas extraction (LGE)

Liquefied gas extraction (LGE) is an innovative method for extracting bioactive compounds from seaweed using gases like propane or butane in their liquefied state under moderate pressure. This technique is particularly effective for recovering lipophilic compounds such as fatty acids, pigments and sterols. LGE offers advantages such as low operating temperatures, which help to preserve thermolabile compounds and minimal solvent residues, resulting in cleaner extracts. The process is efficient, environmentally friendly and requires less

energy compared to conventional solvent-based methods. Optimization of parameters like pressure, temperature and gas type is essential

to maximize extraction efficiency for targeted compounds (Perez-Vazquez *et al.*, 2023).

Table 1: Properties of seaweeds

Mineral compounds	<i>Spatoglossum asperum</i>	<i>Ulva reticulata</i>	<i>Sargassum myriocystum</i>	<i>Ulva lactuca</i>	<i>Kappaphycus alvarezii</i>
Manganese (mg/l)	Not known	108.25	115.2	108.30	2.50
Zinc (mg/l)	0.39	1.25	0.218	1.01	0.62
Iron (mg/l)	392.55	5.22	0.52	0.37	10.59
Potassium %	287.53	175.20	200	113	1.97
Sodium (mg/l)	454.98	295.08	68	185	0.5 %
Calcium (mg/l)	149.44	158.52	32	195.26	460.11
References	Parthiban <i>et al.</i> (2013)	Ganapathy Selvam and Sivakumar (2014)	Kalaivanan and Venkatesalu (2012)	Gireesh <i>et al.</i> (2011)	Rathore <i>et al.</i> (2009)

4. Bioactive compounds from seaweeds

4.1 Polyunsaturated fatty acids

Fatty acids are organic molecules composed of a long hydrocarbon chain attached to a carboxyl group. Depending on the presence or absence of double bonds in the hydrocarbon chain, they are categorized as either saturated or unsaturated. Polyunsaturated fatty acids (PUFAs) contain multiple double bonds and are considered important long-chain unsaturated fatty acids. Among these, omega-3 fatty acids hold particular nutritional value and are commonly found in foods in the form of α -linolenic acid (ALA, C18:3, n-3) (Kalogeropoulos *et al.*, 2010). Marine microalgae are considered major producers of omega-3-rich algal oils, particularly species belonging to the Thraustochytriaceae and Cryptocodiniaceae families (Maltsev and Maltseva, 2021). Genera such as *Cryptocodium*, *Schizochytrium*, *Thraustochytrids*, and *Ulkenia* are commonly utilized for commercial production of valuable fatty acids (Molino *et al.*, 2018).

4.2 Carotenoids

Carotenoids have gained considerable attention due to their strong antioxidant and antimicrobial properties. These compounds are widely incorporated into dietary supplements, enriched food products, animal feed, pharmaceuticals and cosmetic formulations, as they are associated with reducing the risk of various health disorders, including cardiovascular conditions, eye-related diseases, and certain cancers (Francavilla *et al.*, 2010). Several marine algae species are known to contain significant amounts of carotenoids, such as *Ascophyllum nodosum*, *Cladosiphon okamuranus*, *Fucus serratus*, *Chaetoseris sp.*, *Ishige okamurae*, *Ecklonia stolonifera*, *Himantalia elongata* and *Fucus vesiculosus* (Da Vaz *et al.*, 2016).

4.3 Phenolic compounds

The marine algae represent a bountiful source of a variety of phenolic compounds, which include phenolic acids, tannin, flavonoid and catechin. More specifically, brown seaweed of the Phaeophyceae group is characterized by high levels of phlorotannins which are complex polymers of phloroglucinol (1,3,5-thiobenzene). Algae of Rhodophyceae and Chlorophyta, which are red and green respectively, tend to have a different phenolic composition (they contain phenolic acid, flavonoid and bromophenols). The biological effects attributed to the polyphenolic constituents that are isolated by seaweeds include antimicrobial, anticancer, antiviral, anti-obesity,

antiproliferative, antidiabetic, anti-inflammatory and antioxidant (Gomez-Guzman *et al.*, 2018). One of them, phlorotannins, is a hallmark of brown algae (Lomartire *et al.*, 2021). Furthermore, all ubiquitous flavonoid rutin, quercetin and hesperidin are observed among several genera of seaweeds, including Chlorophyta, Rhodophyta and Phaeophyceae (Santos *et al.*, 2019).

4.4 Antimicrobials

Recent studies highlight that algae-derived compounds possess a wide spectrum of biological activities, including antibacterial, antiviral, antioxidant, antifouling, anti-inflammatory, cytotoxic and antimutagenic effects. The evidence of the antimicrobial potential of marine algae was provided by Sameeh *et al.* (2016), who examined extracts from *Padina boryana* and *Enteromorpha* sp. possess substantial total phenolic and flavonoid contents and exhibit strong antibacterial activity against multiple pathogenic organisms. Tuney *et al.* (2006) reported that the antibacterial property of seaweed extracts are largely due to the presence of active chemical constituents such as flavonoids, triterpenoids, and phenolic compounds, which may also contain free hydroxyl groups contributing to their bioactivity. Cyanobacteria also produce several notable cytotoxic antibiotics, including acutiphycins, indolecarbazoles, mirabilene isonitriles, paracyclophanes, scytophycins, tantazoles, tolytoxin, toyocamycin and tubercidin (Mena *et al.*, 2021).

5. Plant growth regulators from seaweeds

In the mid of 1980s, resurgence in algal hormones was noticed and all the phytohormones known in higher plants have been found in algae.

5.1 Auxins

Auxins have been detected in a wide range of algal groups, including brown algae such as *Macrocystis* and *Laminaria*, red algae like *Botryocladia*, green algae including *Enteromorpha*, *Chlorella*, and *Cladophora*, as well as in blue-green algae such as *Oscillatoria* (De Smet *et al.*, 2011). The concentration of auxins in algal tissues varies with both developmental stage and seasonal changes, with the highest levels typically found in vegetative tissues during the summer. A plant growth-promoting compound, 3-(hydroxyacetyl) indole has been identified in the red alga *Prionitis lanceolata*. Similarly, *Nostoc muscorum* isolated from paddy fields exhibited auxin-like effects comparable to indole-3-acetic acid. Extracts of several seaweeds including *Padina*, *Sargassum*, *Turbinaria* and *Champia*, contain auxins in their bioactive fractions (Kumar and Mohan, 1994).

5.2 Gibberellins

Gibberellins are key plant hormones that regulate multiple developmental processes, including seed germination, stem elongation, leaf expansion and the formation of flowers and seeds. Chromatographic studies have confirmed the presence of active gibberellins GA and GA₃, along with the inactive form GA₃, in tissue extracts of *Fucus vesiculosus* and *Fucus spiralis*. Stirk *et al.* (2013) also documented endogenous gibberellins in the microalgae *Raphidocelis subcapitata* and *Scotiellopsis terrestris*. More recently, eighteen different gibberellins were identified in both the stipe and frond tissues of the kelp *Ecklonia maxima*. Additionally, accumulating evidence suggests that plant hormones interact with one another. For instance, gibberellins and auxins often function cooperatively with auxin contributing to the positive regulation of gibberellin levels (Verhage, 2010).

5.3 Cytokinins

A wide range of cytokinins, including zeatin, zeatin riboside, and isopentenyl adenosine, has been detected in different algal extracts. Green microalgae such as *Protococcus*, *Chlorella*, and *Scenedesmus* contain several basic cytokinins, including free cytokinins like isopentenyl adenosine and zeatin, along with their riboside and ribotide conjugates. In *Euglena gracilis*, the chloroplasts possess tRNA that exhibits cytokinin activity and contain multiple cytokinins such as IPA, 2-methylisopentenyladenine, and 2-methylisopentenyladenosine. The cyanobacterium *Arthonema africanum* has also been reported to produce isopentenyl adenosine. In addition, many algal groups synthesize aromatic cytokinins (topolins). The occurrence of both isoprenoid and aromatic cytokinins, along with their various conjugated forms, across numerous algal species suggests the presence of complex hormonal regulatory systems within algae. Evidence indicates that cytokinin biosynthesis in algae may follow pathways distinct from those in higher plants. Studies on *Arthonema africanum* have also shown daily fluctuations in endogenous cytokinin levels, likely reflecting changes in cellular physiological conditions throughout different phases of the culture's life cycle (Zizkova *et al.*, 2017).

5.4 Brassinosteroids

Brassinosteroids have recently been established as an important group of plant hormones, functioning both as promoters of plant growth and as key regulators in enhancing tolerance to various environmental stresses. In the microalga *Chlorella vulgaris*, seven brassinosteroids-teasterone, typhasterol, 6-deoxoteasterone, 6-deoxytyphasterol, 6-deoxocastasterone, castasterone, and brassinolide have been identified (Stirk *et al.*, 2018). Likewise, the green alga *Hydrodictyon reticulatum* contains 24-epicastasterone and 28-homocastasterone. The concentrations of these hormones in algal cells, ranging from 0.3 to 4.0 µg/kg fresh weight, are comparable to the levels typically found in higher plants (Zerun *et al.*, 2025).

6. Phytochemical and phytomedicinal properties of seaweeds

Seaweeds, including green, brown and red algae are rich sources of diverse bioactive phytochemicals with significant nutraceutical and therapeutic potential. They contain essential minerals, vitamins (such as A, B-complex, C, D, E and K), amino acids, λ 3 fatty acids, and an array of secondary metabolites including polyphenols, sulfated polysaccharides, pigments, sterols and peptides (El-Beltagi *et al.*, 2022). The major phytochemical classes responsible for their

biological activities include sulfated polysaccharides such as fucoidans and alginates from brown seaweeds, carrageenans and agars from red seaweeds and ulvans from green seaweeds and phenolic compounds, particularly phlorotannins abundant in brown algae. Pigments such as fucoxanthin, β -carotene, chlorophylls and phycobiliproteins further contribute antioxidant and chemopreventive effects (Xie *et al.*, 2023). Pharmacologically, seaweed-derived compounds have demonstrated that antioxidant, anti-inflammatory, anticancer, antidiabetic, antimicrobial, antiviral, anticoagulant and it possess immunomodulatory effects. Intake of seaweeds or isolated bioactive fractions is linked with mitigation of chronic diseases including diabetes, obesity, cardiovascular disorders, certain cancers, digestive and neurodegenerative conditions (Kumar *et al.*, 2021). Overall, the rich phytochemical composition and wide-ranging pharmacological benefits position the seaweeds as valuable marine resources for dietary, pharmaceutical and agricultural innovations.

7. Variation in phytochemical profiles among green, brown and red seaweeds

Green seaweeds (Chlorophyta) are characterized by high levels of chlorophyll a and b pigments, along with carotenoids such as lutein and β -carotene. They typically have moderate to high total phenolic and flavonoid contents, often higher than those of red seaweeds, providing strong antioxidant activity. Their sulfated polysaccharides mainly include ulvans, which exhibit antioxidant and immune modulatory effects. Green seaweeds also have cellulose-rich cell walls (Venketa Nagendra Prasad, 2024).

Brown seaweeds (Phaeophyceae) contain characteristic pigments, including chlorophyll a, c, and the carotenoid fucoxanthin, which are responsible for their brown color and bioactivities such as antioxidant and anti-inflammatory effects. They are rich in sulfated polysaccharides, including fucoidan, alginate and laminarin, which display antiviral, anti-inflammatory and anticancer properties. Brown seaweeds also have high phenolic content, notably phlorotannins, which confer potent antioxidant and neuroprotective activities (El-Beltagi *et al.*, 2022).

Red seaweeds (Rhodophyta) contain chlorophyll a and unique phycobiliproteins, such as phycoerythrin and phycocyanin, which give them their red coloration and strong antioxidant properties. Their sulfated polysaccharides primarily include carrageenans, agars, and porphyrans, known for their gelling, thickening, and antiviral activities. Phenolic compounds such as flavonoids and tannins are also present, contributing to antioxidant and anti-inflammatory effects. Red seaweeds often have higher amounts of polyunsaturated fatty acids compared to green and brown types (Premarathna *et al.*, 2022). This distinct phytochemical variation is linked to the different species' ecological roles, pigment requirements for photosynthesis and evolutionary adaptations. Such diversity underpins the unique applications of each seaweed type in nutrition, medicine and agriculture.

8. Mechanism: Molecular and metabolic pathway

In plants, seaweed-derived bioactive compounds act as biostimulants and defense elicitors through several molecular and metabolic pathways. The molecular mechanisms induced by seaweed extracts represent a distinct mode of action beyond traditional hormone-based growth promotion, involving complex signaling and gene regulatory networks modulated by diverse bioactive molecules. They

also reprogram the transcriptome to upregulate genes involved in defense (PR-proteins, chalcone synthase), secondary metabolite biosynthesis, nutrient uptake and stress tolerance (Sujeeth *et al.*, 2022). They activate stress-response pathways through signalling molecules such as salicylic acid, jasmonic acid and ethylene, which induce systemic acquired resistance (SAR) and induced systemic resistance (ISR) against pathogens. They also enhance antioxidant enzyme activities, including peroxidase, polyphenol oxidase, chitinase, β -1, 3-glucanase and phenylalanine ammonia-lyase, thereby reducing oxidative stress and improving defense capacity (Kumar *et al.*, 2024). Seaweed compounds modulate phytohormones such as auxins, cytokinins, gibberellins, abscisic acid and brassinosteroids, which regulate growth, development, senescence and responses to abiotic stresses. These extracts also improve nutrient uptake and photosynthetic efficiency, leading to enhanced plant growth and yield under both normal and stress conditions (Ayodeji *et al.*, 2022). Polysaccharides such as laminarin, fucoidan, ulvan and carrageenans act as elicitors, stimulating immune response pathways, including the oxidative burst and production of defensive phytoalexins (Agarwal *et al.*, 2021). Under stressful conditions, application of seaweed extracts substantially increases the concentration of specific phenolic acids and flavonoids, such as syringic acid, rutin, p-coumaric acid, cyanidin-3-glucoside and chlorogenic acid, while other compounds such as quercetin, caffeic acid, sinapic acid and ellagic

acid are significantly reduced (Kapur *et al.*, 2024). Collectively, these molecular actions enhance plant resilience against biotic and abiotic stresses while promoting growth and quality traits.

9. Methods of application

Seaweeds are applied as fertilizers using various methods, including seed treatment, foliar spray, granules, manure, and powder (Immanuel and Subramanian, 1999); seedling dip (Lingakumar *et al.*, 2002); soil drenching; soil and subsurface fertigation; or by combining seaweeds with soil, sand, straw or composted peat and other organic waste to enhance soil nutrient levels necessary for crop growth (Mirparsa *et al.*, 2016). Field and soil conditions benefit from the addition of seaweeds in sufficient amounts as organic fertilizers, supplying essential nutrients such as N, P, K along with Ca, Mg, Fe, and Zn (Badar *et al.*, 2015). The presence of growth-promoting substances like phenylacetic acid, gibberellins and auxins (Sivasankari *et al.*, 2006), as well as other micronutrients, can improve germination and seedling vigor even at low concentrations of seaweed extracts (Layek *et al.*, 2015). The effectiveness of seaweed extracts depends on dosage, frequency, application method and timing, which must be aligned with soil type, climate, agronomic practices and crop developmental stages. Proper application is essential, as higher doses of seaweed extract can produce phytotoxic symptoms, resulting in yield loss (Spinelli *et al.*, 2010).

Table 2: Effect of seaweed extracts on cereals, pulses, oilseeds and medicinal crops

Crop	Seaweeds	Effects	References
Paddy	<i>S. wightii</i> and <i>P. boergeseni</i>	Improved germination, seedling length and vigour	Padmavathi <i>et al.</i> , 2021
Wheat	Ulvan (<i>Ulva fasciata</i>)	Triggers defense mechanisms	De Borba <i>et al.</i> , 2022
Blackgram	<i>Sargassum Polycystum</i> <i>Asparagopsis taxiformis</i> <i>Sargassum myricocystum</i>	Improved germination, plant height, dry weight, total chlorophyll, leaf area index, vigour and yield	Sujatha <i>et al.</i> , 2013
Cowpea	<i>Ulva lactuca</i>	Increased root and shoot length, fresh weight, α -amylase, β -amylase, chlorophyll and carotenoids content	Lakshmi and Sundaramoorthy, 2010; Gireesh <i>et al.</i> , 2011
Bean	<i>Fucus spiralis</i> and <i>Ulva rigida</i>	Increased shoot and root length	Latiq, 2013
Cluster bean	<i>Sargassum wightii</i>	Enhanced the yield (10 to 20%) and biochemical parameters	Vijayan <i>et al.</i> , 2014
Greengram	<i>Portieria hornemannii</i>	Higher germination and plant growth	Karthick and Jayasri, 2023
Sesame	<i>Sargassum myricocystum</i> <i>Caulerpa racemosa</i>	Increased seedling length, dry matter production	Sujatha <i>et al.</i> , 2013; Thirumalai Kannan, 2013
Groundnut	<i>Hypnea musciformis</i>	Total chlorophyll and protein content got increased	Ganapathy Selvam and Sivakumar, 2014
Soybean	<i>Kappaphycus alvarezii</i> , <i>A. nodosum</i>	Improved yield parameters, nutrient uptake and drought tolerance level	Martynenko <i>et al.</i> , 2016
Sunflower	<i>A. nodosum</i>	Improved seed germination and seedling growth	dos Santos <i>et al.</i> , 2019
Ashwagandha (<i>Withania somnifera</i> L.)	Seaweed fertilizers / extracts	Improved root length and thickness, increased fresh root yield (584 kg/ha) and dry root yield (180 kg/ha)	Giridharan and Sindhu, 2025
Turmeric (<i>Curcuma</i>)	Seaweed extract (foliar or <i>longa</i> L.)	Improved nutrient absorption and curcumin content (soil application)	Ogbuehi and Ukaoma, 2018
Neem (<i>Azadirachta indica</i> A.)	Seaweed-derived biostimulants	Enhanced plant vigour and higher azadirachtin content	Ganesan <i>et al.</i> , 2019
Saffron (<i>Crocus sativus</i> L.)	Red seaweed extracts (foliar application)	Stimulated the vegetative growth and corm multiplication	Vaghela <i>et al.</i> , 2023
Sweet basil <i>Ocimum tenuiflorum</i> L.	Red seaweed extracts (foliar application)	Boosted the biomass and essential oil yield	Thakur <i>et al.</i> , 2025

9.1 Impact of seaweed extracts on soil

Seaweed manure is more beneficial than chemical fertilizers because it contains a higher amount of organic matter (10-100%), aids in moisture retention, provides minerals and makes them available to plant roots in the upper soil layer (Jothinayagi and Anbazhagan, 2009). It contains nutrients such as polysaccharides and trace elements, which can stimulate microbial growth and enhance the proportion of beneficial bacteria in the soil, promoting overall microbial activity. Seaweed manure is particularly valuable because it contains a significant amount of alginate, which acts as a soil conditioner and alginic acid, which accelerates bacterial decomposition of organic matter, thereby enhancing humus and nutrient availability in the soil. During the decomposition of *Sargassum horneri*, nitrate, ammonium, total nitrogen, and phosphorus are released and can chelate with major cations such as Na^+ , Ca^{2+} , Mg^{2+} and K^+ to form aggregates enriched with nutrients. This process improves soil structure and stimulates soil microbial activity (Zodape, 2001;

Table 3: Effect of seaweed extracts on biotic stress

Crop	Seaweeds	Effects	References
Pulses	<i>Sargassum</i> spp.	<i>Macrophominaphaseolina</i> and <i>Rhizoctonia solani</i>	Sujatha <i>et al.</i> , 2014
Brinjal	<i>Sargassum latifolium</i> , <i>Hydroclathrus clathratus</i> and <i>Padina gymnospora</i>	<i>Fusarium solani</i> , <i>Rhizoctonia solani</i>	Ibraheem <i>et al.</i> , 2017
Tomato and Sweet pepper	<i>A. nosdum</i>	<i>X. campestris pvvesicatoria</i> , <i>Alternaria solani</i>	Ali <i>et al.</i> , 2016
Tomato	<i>S. tenerrimum</i>	<i>M. phaseolina</i>	Khedia <i>et al.</i> , 2020
Wheat and Drum wheat	<i>A. nosdum</i>	<i>Zymosporiatritici</i>	Somai-Jemmali <i>et al.</i> , 2020

Table 4: Effect of seaweed extracts on insecticidal properties

Crop	Seaweeds	Effects	References
Cotton	<i>Ulva intestinalis</i> <i>Ulva lactuca</i> , <i>Cladophora glomerata</i> , <i>Ulva lactuca</i>	<i>Spodoptera littoralis</i>	Abbassy <i>et al.</i> , 2014; Saber <i>et al.</i> , 2018
Cowpea	<i>Sargassum tenerrimum</i> and <i>Gracilaria corticata</i>	<i>Aphis craccivora</i>	Thawfeeq Ahamed <i>et al.</i> , 2022
Cabbage and Cauliflower	<i>Gracilaria edulis</i> , <i>Sargassum</i> sp. <i>Stoechospermum marginatum</i>	diamond back moth, <i>Plutella L. xylostella</i>	Liza <i>et al.</i> , 2023

11. Effect of seaweed extracts against biotic and abiotic stress

11.1 Effect of seaweed extracts against biotic stress

Pathogenic fungi, bacterial agents, and insect vectors are biotic factors that significantly impact crop production and quality, causing losses of up to 14% of annual global crop yields. Moreover, the emerging effects of climate change have increased the spread of plant pathogens, raising the risk of diseases and crop yield variability (Secretariat *et al.*, 2021). Extracts of marine algae, including *Sargassum tenerrimum* and *Padina tetraströmatica*, exhibited nematocidal activity against *Meloidogyne javanica* (Khan *et al.*, 2015). Brown algae such as *Sargassum vulgare*, *Dictyopteris membranaceae* and *Dictyodictoma* were tested against phytopathogens (*Aspergillus niger*, *Cladosporium cladosporioides*, *Alternaria alternata*, *Fusarium oxysporum* and *Penicillium citratum*) and antifungal compounds present in the extracts reduced pathogen levels (Khalil *et al.*, 2015). Foliar application of *Sargassum* spp. extracts decreased the incidence

of powdery mildew in tomato plants (Sabaihat *et al.*, 2015). Seaweed extracts contain polysaccharides such as alginates, ulvans, fucans, carrageenans, and laminarins, which act as natural elicitors of plant defense mechanisms by activating the salicylic acid (SA), jasmonic acid (JA), and ethylene signaling pathways and laminarin in brown seaweeds promotes the activity of key enzymes, including PAL and lipoxygenase (LOX), which are vital for antimicrobial defense responses (Klarzynski *et al.*, 2003; Saucedo *et al.*, 2015). These marine resources contain a variety of bioactive compounds, including polysaccharides, proteins, essential amino acids, dietary fibers, polyunsaturated fatty acids and bioactive peptides (Okolie *et al.*, 2018). Multiple studies have demonstrated these protective effects across different crops and pathogens. For example, when applied to sweet pepper and tomato plants, *Sargassum* spp. extracts reduced infections by *Alternaria* and *Xanthomonas*, which is linked to increased activity of defense enzymes such as peroxidase, phenylalanine ammonia lyase (PAL) and β -1,3-glucanase, along with upregulation

10. Significance of seaweed application on plant growth

The use of seaweed extracts has been demonstrated to enhance plant growth, yield, and overall crop quality. Extracts from various seaweeds, including *Ascophyllum* spp. *Sargassum* spp. *Ulva* spp. *Padina* spp. *Caulerpa* spp. *Kappaphycus* spp. and *Gracilaria* spp. have been applied to diverse agricultural crops. These applications have been shown to improve seed germination, stimulate vegetative growth, increase yield, enhance crop quality, and strengthen plant tolerance to both biotic and abiotic stresses. The specific effects of these seaweed extracts are summarized in the following tables.

of defense genes (PR1-a, ETR-1), particularly those mediated by jasmonic acid signaling (Ali *et al.*, 2022). Natural bioactive chemicals found in seaweeds include terpenes, steroids, aromatics such as acetogenins, compounds derived from amino acids such as phlorotannins and other polymeric materials and a wide variety of brown seaweed species have thus been shown to be effective in managing plant diseases (Pirez *et al.*, 2022).

11.2 Effect of seaweed extracts against abiotic stresses

Agricultural systems are highly influenced by climatic conditions and abiotic stress is a major threat that can significantly reduce crop yields. Drought and salinity, in particular, are responsible for substantial crop losses, sometimes causing reductions of up to 50% in yield and productivity (Gull *et al.*, 2019). Therefore, it is crucial to develop strategies to mitigate the adverse effects of abiotic stress on crops. Seaweed extracts have been shown to provide protective effects against abiotic stresses and are emerging as a promising approach to enhance plant resilience under challenging environmental conditions, including salinity (Abdelaziz *et al.*, 2024). Crops treated with seaweed extracts have demonstrated recovery from heat and frost damage and increased survival under drought and saline conditions. These extracts are rich in sustainable, eco-friendly bioactive compounds that promote plant growth and development. Rice plants treated with *A. nodosum*, *Kappaphycus*, and *Sargassum* spp. showed improved nutrient uptake under drought conditions. Seaweed extract-treated plants maintained higher relative water content, improved water-use efficiency, better stomatal conductance, and reduced

transpiration rates under drought conditions (Santaniello *et al.*, 2017). Wheat varieties treated with *Kappaphycus alvarezii* under salinity and drought stress exhibited enhanced tissue water content and accumulated osmoprotectants such as proline, amino acids and total proteins (Patel *et al.*, 2018). *Ulva lactuca*-treated rapeseed grown under severe salinity showed improved growth. Maize plants treated with *K. alvarezii* mitigated water stress and displayed increased antioxidant activity (Trivedi *et al.*, 2018). Similarly, soybean and wheat plants treated with seaweed extracts exhibited reduced water loss and faster recovery from drought stress (Sharma *et al.*, 2019). Enhanced growth was observed in rice and wheat cultivated under saline conditions (Zou *et al.*, 2018; Liu *et al.*, 2019). Durum wheat plants treated with *Ulva rigida* under saline conditions exhibited significantly enhanced antioxidant activity (Latique *et al.*, 2021). Maize and black-eyed pea seeds treated with *Ulva fasciata* and *Laurencia obtusa* exhibited increased tolerance to salinity stress. Okra seeds treated with *A. nodosum* under drought stress demonstrated enhanced anthocyanin and antioxidant activities (Ali *et al.*, 2022). Freezing stress also negatively affects plant growth and agricultural productivity and ice formation within intercellular and extracellular spaces can lead to cell death. Bioactive compounds in extracts from *A. nodosum* have been reported to mitigate cold stress. Barley treated with *A. nodosum* extract (ANE) under cold stress showed increased frost tolerance and hardness. Tobacco cultivars treated with *A. nodosum* extracts exhibited significant freezing stress tolerance, attributed to the upregulation of key freezing tolerance genes (Zamani *et al.*, 2019).

Table 5: Effect of seaweed extracts on abiotic stresses

Crop	Stress	Seaweed Species	Effect	References
Wheat	Drought	<i>Gracilaria dura</i>	Dehydrin involved	Sharma <i>et al.</i> , 2019
Maize	Drought	<i>K. alvarezii</i>	Expression of defence genes	Kumar <i>et al.</i> , 2020
Spinach	Heat	<i>A. nodosum</i>	Low melonaldihyde and hydrogen peroxide production	Anjos <i>et al.</i> , 2020
Cowpea	Drought	Kelpak	Increased photosynthetic pigments	Voko <i>et al.</i> , 2022
Mustard	Drought	<i>A. nodosum</i>	Increased proline glycine betaine content	Sujata <i>et al.</i> , 2023
Tomato	Drought	<i>A. nodosum</i>	Osmo protectants	Kanojia <i>et al.</i> , 2024

12. Biosafety, toxicology and quality control

Biosafety, toxicology and quality control are essential aspects in the development and application of seaweed-derived products. Seaweeds are widely regarded as abundant and generally safe marine resources, with most of their bioactive compounds exhibiting very low phytotoxicity in both human and animal studies. Polysaccharides such as fucoidan, carrageenan and agar, along with phenolic compounds like phlorotannins, have demonstrated minimal toxicity and are broadly recognized as safe for consumption and pharmaceutical use (Bharadwaj *et al.*, 2022). Edible seaweeds also provide a rich source of essential nutrients, vitamins, minerals and polyunsaturated fatty acids, supporting their expanding use in nutraceutical, pharmaceutical, and cosmetic industries. Despite this favorable safety profile, continuous toxicological assessments, contaminant analysis and clinical studies remain necessary to confirm the safety of seaweed compounds for therapeutic and agricultural applications (El-Beltagi *et al.*, 2022). Long-established seaweed-derived compounds, including carrageenan, alginic acid, agar and fucoidan, have been widely used in

food and topical formulations due to their stabilizing, thickening and protective properties, with an extensive history of safe use (Lomartire and Goncalves, 2022). With the discovery of new metabolites and functional biomolecules, ongoing research and preclinical studies are crucial to determine optimal dosages, long-term safety, and therapeutic efficacy (Al-Hashdy *et al.*, 2025). In agriculture, seaweed extracts act as biostimulants and protective agents, exhibiting low phytotoxicity when properly formulated and applied (Perez *et al.*, 2016). Overall, seaweed-derived compounds display favorable biosafety characteristics and low toxicity, provided they are well-characterized, sourced from uncontaminated environments and continuously evaluated using standardized safety validation protocols. Their expanding applications in human health and agriculture are further supported by toxicological data, advanced bioinformatics and screening technologies, although vigilance for environmental contaminants remains crucial (Francisco de Souza, 2025).

Quality control is fundamental for ensuring the safety and efficacy of seaweed products, especially since seaweeds can bioaccumulate

environmental pollutants. Monitoring for heavy metals, pesticides, and microbial contaminants is essential to maintain product safety and meet regulatory standards (Sivakumar and Kandasamy, 2025). Modern quality management systems emphasize sustainable sourcing, green extraction processes and continuous monitoring of processing conditions to improve yield, minimize environmental impact, and preserve product integrity (Peraira and Cotas, 2024). In summary, the quality control of seaweed-derived products relies on rigorous analytical testing, contaminant screening, standardized production methods and sustainability-focused practices, ensuring safe, reliable and high-quality products for pharmaceutical, nutraceutical and agricultural applications (Valverde *et al.*, 2022).

13. Future perspectives

As renewable bioresources, seaweeds and their by-products provide a range of organic inputs to meet the growing demands of modern agriculture. Extraction techniques for different seaweed varieties need to be optimized to develop commercially viable formulations. Integrated extraction systems that combine multiple methodologies should also be explored to enhance efficiency, yield and product consistency. The efficacy of seaweed extracts under controlled and field conditions, along with their underlying mechanisms of action, requires detailed investigation. Improving application methods and optimizing concentrations for different crops under diverse environmental conditions could further enhance their benefits. The unique bioactive compounds in seaweeds, which promote plant growth, improve tolerance to both biotic and abiotic stresses and enhance overall productivity, warrant comprehensive study. From a commercialization perspective, there is a growing global market for seaweed based agricultural products, driven by increasing demand for eco-friendly biostimulants and organic inputs. Additionally, regulatory frameworks play a critical role in the commercialization of seaweedbased products. Compliance with agricultural and environmental regulations, registration requirements for biofertilizers and biostimulants and adherence to safety standards are essential to facilitate widespread acceptance among farmers and stakeholders. Assessing the economic performance of seaweed-based products, evaluating their market potential and establishing clear regulatory pathways will be crucial for their sustainable adoption in modern agriculture, supporting productivity, crop resilience, soil health and long-term ecological balance while reducing dependence on chemical fertilizers and pesticides.

14. Conclusion

Growing awareness of environmental conservation, along with consumer demand for safe and chemical-free food, has driven global interest in sustainable and eco-friendly agricultural systems. Seaweeds are rich in plant growth regulators, including auxins, cytokinins, gibberellins, brassinosteroids, betaines and abscisic acid, which are essential for cell division, photosynthesis, nutrient assimilation, root development and stress tolerance in crops. In addition, seaweeds contain a wide array of bioactive compounds, such as polysaccharides (agar, alginic acid, fucoidans, laminarans, ulvans), phenolics and polyphenols (*e.g.*, eckol, phloroglucinol, 4-bromophenol), proteins and peptides (taurine, domoic acid), sterols (fucosterol, ergosterol, cilonasterol, β -sitosterol) and carotenoids (lutein, fucoxanthin, β -carotene). These phytochemicals possess strong phytomedicinal properties, including antioxidant, antimicrobial, antiviral, anti-inflammatory and antifungal activities, which enhance plant immunity

and resilience under adverse environmental conditions. In several Asian countries, including China, Japan and Korea, seaweed species such as *Porphyra*, *Monostroma* and *Ulva* have long been used as nutritious food sources, although their potential remains underexploited in India. Incorporating protein-rich marine algae into diets can also help address nutritional deficiencies, such as infant malnutrition. In agriculture, liquid extracts from seaweed species including *Ascophyllum*, *Sargassum*, *Fucus*, *Laminaria*, *Turbinaria*, *Kappaphycus*, *Gracilaria*, *Sarconema* and *Ulva* have shown substantial benefits in improving crop growth, yield, fruit quality, soil fertility and microbial activity. These extracts also delay senescence, enhance nutrient use efficiency and provide protection against stresses such as drought, salinity, chilling injury and diseases across agricultural crops. Overall, seaweed-based products offer a natural and environmentally sustainable solution for modern agriculture, supporting productivity, crop resilience, soil health and long-term ecological balance while reducing reliance on chemical fertilizers and pesticides.

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Conflict of interest

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

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