

SEAWEED-BASED BIOFORMULATION FOR SUSTAINABLE PLANT DISEASE MANAGEMENT - A REVIEW

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ABSTRACT

Seaweed- derived bioformulations have emerged as promising sustainable alternative approaches for managing plant diseases in modern agriculture. Growing concern about the excessive use of synthetic pesticides- including environmental contamination, the development of pathogen resistance, and adverse effects on non-target beneficial organisms has intensified the search for eco- friendly, bio- based solutions. Marine macroalgae, primarily classified into Chlorophyceae, Phaeophyceae, and Rhodophyceae, are rich in sources of diverse bioactive compounds such as polysaccharides, phenolics, phytohormones, and various secondary metabolites. These compounds play a critical role in modulating plant defense mechanisms and suppressing a wide range of phytopathogens. This review provides a comprehensively discusses the diversity of seaweed species, major extraction methodologies, and the key bioactive compounds involved in disease suppression. Special attention is given to polysaccharides, including laminarin, carrageenan, fucoidan, alginate, and ulvan, which trigger plant immune responses such as systemic acquired resistance (SAR) and induced systemic resistance (ISR). In addition to their role in defense induction, certain seaweed extracts exhibit direct antifungal, antibacterial, and antiviral activities against economically important plant pathogens. Recent advances in nano- formulation, along with the increasing availability of commercial seaweed- based products, further highlight their potential in integrated disease management strategies. Overall, seaweed- derived bioformulations represent an effective, environmentally sustainable approach to enhancing crop protection and improving plant health within agricultural ecosystems

KEYWORDS: Seaweed, Bioformulation, Plant diseases, SAR, ISR, Sustainability

1. INTRODUCTION

Highlights

- □ Seaweed bioformulations from Chlorophyceae, Phaeophyceae offer ecofriendly use.
- □ Rhodophyceae macroalgae provide bioactives that boost plant defense responses.
- □ Describes from conventional to advanced seaweed metabolite extraction methods.
- □ Polysaccharides from these families induce SAR and ISR in crops effectively.
- □ Seaweed extracts show antifungal, antibacterial, and antiviral properties.
- □ Nano formulations improve use in sustainable disease management systems.

Conventional agricultural practices predominantly rely on chemical fertilizers to supply crops with essential mineral nutrients. However, the prolonged use of these chemical input adversely affects soil fertility and microbiota leading to accumulation of residues in the soil that reach toxic concentration for plants. Beneficial soil microbiome, produces natural volatile compounds with antimicrobial activity against common plant pathogens (1) . In recent years, the search for novel bioactive substances from marine sources, including microalgae, seaweed, and crustaceans, has gained significant attention. Seaweed is a group of macroalgae that lack true roots, stems, and leaves (2). Instead, its thallus and holdfast facilitated attachment and nutrient absorption (3). Seaweed, often referred to as “marine algae, is a member of the algal group and ranges in size from microscopic single cells to some of the biggest plants known to man, such as gigantic seaweeds, which create dense forests in coastal water (4). Approximately 10,000 species comprise the macroalgae, which account for 10% of global marine production. The marine seaweed is a member of the Rhodophyceae (red), Phaeophyceae (brown), and Chlorophyceae (green) families. Marine macroalgae is a great source of bioactive chemicals with a wide spectrum of biological activity, including antibacterial and antifungal properties (5). Additionally, these extracts have been employed in agriculture as soil conditioners to increase crop yield (6). Seaweeds are abundant in polyphenolic chemicals, unsaturated fatty acids, and dietary fiber. Numerous seaweed formulations have been shown to improve human health, including the treatment of diabetes (7). Plant diseases caused by Fungi, bacteria, viruses and nematodes inflict severe yield losses and threaten food security. Annual crop losses to disease are estimated

at over 30% globally, amounting to hundreds of billions of dollars in lost production (8). Conventional disease management strategies rely heavily on synthetic pesticides, which have raised serious concerns regarding environmental pollution, pathogen resistance, non-target effects, and human health risks (9). In response to these challenges, sustainable and eco-friendly alternatives are increasingly being explored, among which seaweed-based bioformulations have emerged as promising tools for plant disease management (10). The impetus for seaweed-based disease management tools is anchored in the broader need to reduce reliance on conventional synthetic pesticides and move toward sustainable intensification approaches that preserve yield and quality of plants while lowering ecological and human health burdens. Reviews spanning seaweed bio stimulants and elicitors consistently position seaweed-derived products as lower-input options that enhance plant resilience to biotic stress, often through host defense activation rather than direct toxicant-like pathogen suppression (11). In this review, “seaweed-based bioformulation” is interpreted deliberately broadly to match current science and product reality. Seaweed supply-chain feasibility matters for any “bio-based” diseases-management approach. The Food and Agriculture Organization (FAO) of the United Nations reports that global fisheries and aquaculture production in 2022 include 37.8 million tons of algae, indicating a large and growing base of algal biomass within aquatic food/biomass systems. While agricultural use competes with food, feed and industrial uses, this scale frames seaweed as a realistic bioresource provides responsible and processing is standardized for agronomic performance. A critical boundary condition for “plant disease management” claims is regulation. In the EU legal framework (Regulation (EU) 2019/1009). “Plant bio stimulant” is defined around stimulation of plant nutrition process, such as improving nutrient use efficiency, abiotic-stress tolerance, quality traits, or nutrient availability, and the related amendments clarify when a product is excluded from plant-protection product regulation. In practice, this means many seaweed products are marketed as bio stimulants even when they confer disease resilience; however, explicit disease-control claims can change regulatory status. National regulatory have echoed this function demarcation in guidance that explain how bio stimulant fit outside plant-protection product framework when aligned to the bio stimulant definition. In India, bio stimulants are regulated under the fertilizer control order system and explicitly include “botanicals extracts, including seaweed extracts” as a category. A major recent regulatory development in India is that provisional registrations were time-bound, as per the government communication, provisional registrations became invalid after 16 June 2025, reflecting a tightening formalization of the sector and raising the bar for data on chemistry, bio efficacy and toxicity for listed products

This review summarizes the diversity of seaweed species used in agriculture, major extraction techniques, important bioactive compounds, and their mechanism of action against fungal, bacterial, and viral plant pathogens. Particular emphasis is placed on key polysaccharides, including laminarin, carrageenan, fucoidan, alginate, and ulvan, which act as potent elicitors of plant defense pathways. In addition, recent advances in nano-formulations and commercially available seaweed-based products are discussed. Overall, seaweed-derived bioformulations represent a promising, environmentally sustainable approach for integrated plant disease management and improved crop resilience.

Previous reviews have discussed seaweed-derived bio stimulants, elicitors and biocontrol potential. The present review extends this literature by integrating the continuum from seaweed source and extraction strategy to bioactive composition, mechanism of disease suppression, formulation and delivery, field performance, commercialization and regulatory constraints. Particular emphasis is placed on distinguishing direct antimicrobial activity from host-defense priming and on identifying the factors responsible for inconsistent efficacy among studies. Thus, this review moves beyond cataloguing seaweed species and bioactive compounds to evaluate the translation of biological activity into reproducible disease-management products.

The literature included in this review was identified through a comprehensive search of major scientific databases, including Web of Science, Scopus, PubMed, Google Scholar and ScienceDirect. Peer-reviewed articles published primarily between 2000 and 2025 were considered, while seminal studies published before 2000 were also included where they provided foundational information on seaweed bioactive compounds or plant disease management. Search terms included combination of: “Seaweed”, “macroalgae”, “bioformulation”, “plant disease”, “plant pathogen”, “biocontrol”, “elicitor”, systemic acquired resistance (SAR)”, “induced systemic resistance (ISR)”, “antifungal”, “antibacterial”, “antiviral”, “polysaccharides”, “laminarin”, “carrageenan”, “fucoidan”, “alginate”, “Ulva”, “nanotechnology”, and “commercial seaweed products”. Studies were selected based on their relevance to seaweed-derived bioformulations for plant disease management, with emphasis on original research articles, review papers, and reports describing extraction methods, bioactive compounds, mechanisms of action, nano formulations, and commercial applications. Non-peer-reviewed sources, duplicate publications, and studies lacking sufficient experimental evidence or direct relevance to plant disease management were excluded.

2. Types of Seaweed

Indian coastal waters support high seaweed diversity, with earlier records documenting 770 species and recent systematic accounts listing 844 species across 217 genera. Red algae dominate (434 species), followed by green (216), brown (191), and yellow-green algae (3). Tamil Nadu harbors the highest number of species (302), followed by Gujarat, Maharashtra, Lakshadweep, Andhra Pradesh, and Goa (12). Seaweeds are broadly classified into three major divisions: Chlorophyceae (green algae), Phaeophyceae (brown algae), and Rhodophyceae (red algae). The classification is based on pigmentation, cellular structure, and related characteristics (12). In terms of pigmentation, green algae contain chlorophyll, red algae are characterized by the presence of phycoerythrin, while brown algae possess xanthophyll pigments, predominantly fucoxanthin, similar to the pigment-based classification observed in higher plants (13).

2.1. Chlorophyceae

Green algae occur in both freshwater and marine habitats and range from unicellular to multicellular forms. Their green color is due to chlorophyll, and because they require ample sunlight, they are mainly found in shallow coastal and near-shore waters (14). Green seaweeds are classified under the phylum Chlorophyta. Common representatives of this group include species belonging to the genera *Enteromorpha*, *Ulva*, *Chaetomorpha*, *Codium*, and *Caulerpa*, which are widely recognized as typical green seaweeds (14). Green seaweeds are recognized for their role in plant disease management due to the presence of sulfated polysaccharides and glycoproteins that function as defense elicitors. Ulvans, the major sulfated heteropolysaccharides of *Ulva* spp., have been shown to induce systemic resistance in several crops by activating defense-related enzymes and genes rather than exerting direct antifungal activity (15). Foliar application of ulvan significantly reduced *Zymoseptoria tritici* infection in wheat through the upregulation of pathogenesis-related proteins, including β -1,3- glucanase and chitinase, and by stimulating jasmonic acid and salicylic acid signaling pathways (15).

Similarly, arabinogalactan protein-like glycoproteins extracted from *Ulva lactuca* were reported to activate immune responses in oilseed rape by inducing hydrogen peroxide accumulation and defense gene expression, leading to enhanced resistance against fungal pathogens (16). A sulfated glycoprotein fraction isolated from *Codium decorticatum* significantly increased phenolic content, lignin deposition, and phenylalanine ammonia-lyase activity in tomato plants, resulting in improved resistance against phytopathogens (17).

2.2. Phaeophyceae

Brown algae are exclusively marine and the fastest-growing seaweeds. They range from simple filaments to highly differentiated thalli, often with air bladders for buoyancy, and their olive to dark brown color is mainly due to fucoxanthin along with chlorophyll a and c (12). Brown algae serve as an important natural source of iodine and potash (18). Phlorotannins have been successfully isolated from several brown seaweeds, including *Fucus spiralis*, *Gongolaria usneoides* (formerly *Cystoseria usneoides*), and *Gongolaria nodicaulis* (formerly *Cystoseira nodicaulis*) (2). Brown algae are rich in phlorotannins, unique polyphenolic compounds that exhibit strong antibacterial and antifungal activity, suggesting a dual mode of action involving both pathogen inhibition and host defense activation (19).

2.3. Rhodophyceae

Except for a few species, red algae are mainly marine and occur as epiphytes, crusts, or fleshy, branched, or blade-like thalli. Red color is due to phycoerythrin and phycocyanin along with chlorophyll a and b, and they are widely used in food products and scientific research (12). The cell walls of red algae consist of cellulose fibrils, rarely xylan fibrils, embedded in a hydrocolloid matrix composed mainly of sulfated polysaccharides classified as agar and carrageenan. In some taxa, calcium carbonate is deposited in the cell wall as either calcite or aragonite (20). Red algae are recognized as a particularly rich natural source of bromine (21). Certain groups of red algae accumulate higher levels of specific sulfated polysaccharides and are therefore classified as agarophytes or carrageenophytes. Agarophytes, which produce agar, include orders such as Gracilariales, Gelidiales, and Ceramiales. In contrast, carrageenophytes, characterized by carrageenan production, comprise most families within the Gigartinales, including Solieriaceae, Hypneaceae, Cystocloniaceae, Caulacanthaceae, Furcellariaceae, Trichocarpaceae, Sphaerococcaceae, Polyideaceae, Kallymeniaceae, Dumontiaceae, and Rhizophyllidaceae (20). Carrageenans extracted from *Kappaphycus* and *Chondrus* species have been shown to induce systemic resistance in plants by activating salicylic acid, jasmonic acid, and ethylene signaling pathways (22). Application of λ - carrageenan significantly reduced viral and fungal diseases by inducing defense-related enzymes such as peroxidase, polyphenol oxidase, and phenylalanine ammonia-lyase (22). Oligo-carrageenans were reported to enhance resistance in tobacco and tomato against viral pathogens by modulating jasmonic acid-responsive genes and suppressing pathogen replication (23). Moreover, carrageenan treatment resulted in increased accumulation of secondary metabolites, including phytoalexins and phenolics, thereby strengthening plant cell walls and restricting pathogen colonization (23). The disease-suppressive effects of red algal polysaccharides are largely attributed to their sulfate content and molecular structure, which enable them to function as pathogen-associated molecular pattern (PAMP) mimics and activate innate immune responses in plants (22). Fig.1 illustrate the major sea weed growing coastal region in Tamil Nadu, India.



Fig.1. Major seaweed growing area in Tamil Nadu

3. Bioactive compounds in Seaweed

Seaweed extracts derived from brown, red, and green macroalgae are rich in diverse bioactive compounds such as polysaccharides, oligosaccharides, phytohormones, polyphenols, and terpenoids, which are capable of inducing plant defense responses and directly suppressing plant pathogens (24,10). These extracts act as bio-elicitors or biostimulants by mimicking pathogen-associated molecular patterns (PAMPs) and priming systemic acquired resistance (SAR) or induced systemic resistance (ISR) pathways in plants (25, 22). For instance, laminarin (a β - 1,3- glucan from brown algae) and Carrageenans (Sulfated galactans from red algae) activate defense- related gene expression associated with phenylpropanoid metabolism and salicylic acid or jasmonic acid signaling pathways, along with enhanced antioxidant enzyme activity, thereby improving resistance against fungal and bacterial diseases (22)

Seaweed has a very high moisture content, which can make up as much as 94% of the biomass. Although marine algae contain nutritional components such as proteins, lipids, carbohydrates, vitamins, and minerals, like other plants, the amounts of these components vary according to the season and the production region (26). Various types of carotenoids, which are potent antioxidants, are present in the extracts and are known to contain a variety of minerals. Additionally, seaweed extract contains phytohormones such as betaines, auxin, gibberellins, cytokinins, and abscisic acid (27).

3.1 Polysaccharides

Marine algae are rich in polysaccharides, including mycopolysaccharides, storage polysaccharides, and cell wall structural polysaccharides (28). Polysaccharides often make up to 76% of the dry weight of seaweed extract and contain a proportionate amount of the most significant forms of algal polysaccharides, including galactans, fucoidan, laminarin, and alginates (10). These algal polysaccharides' ability to activate signaling pathways and strengthen defensive systems in a variety of plants has been greatly influenced by their composition and structure (29). Seaweed contains polysaccharides, including laminarins, fucoidans, carrageenan, and ulvans that function as phytoelicitors and activate plant defense mechanisms and help protect plants against diseases (22). It has been observed that a number of seaweed polysaccharides, such as alginate, carrageenans, and sulfated fucans, have antiviral properties (30). Seaweed-derived alginates are composed of different types of mannuronic(M) and guluronic (G) acids. Sulfated polysaccharides represent the major bioactive constituents found in brown, red, and green seaweed. Among them, carrageenan from red algae, fucoidan from brown algae, and ulvan from green algae are the most prominent groups. These polysaccharides are known to possess diverse biological activities, including antimicrobial, antitumor, antimutagenic, anticoagulant, anti-inflammatory, immunomodulatory, antiviral, and antithrombotic effects, making them valuable for various therapeutic applications (31). Foliar application of λ - Carrageenan has been shown to suppress Tomato chlorotic dwarf viroid through induction of jasmonic acid- mediated defense responses (32).while laminarin treatments enhanced resistance to Tobacco Mosaic Virus in tobacco by activating defense- related genes (33).

3.2 Carrageenans

Carrageenans are structurally complex sulphated polysaccharides that function as important hydrocolloids and are predominantly extracted from various species of red seaweeds (34). They represent the third most widely utilized hydrocolloid globally, following starch and gelatin. In their native state, carrageenans serve as structural components of the cell walls in many red algal species (35). Chemically, they consist of linear polysaccharides chains composed of alternating galactose residues, with varying degrees of sulfation in the form of sulfate half- ester groups attached to the sugar units. These structural features enable them to be water-soluble, produce highly viscous solutions, and maintain stability across a broad pH range (36) . Carrageenans are sulphated galactans classified by the presence of 3,6-anhydrogalactose and by the number and position of sulphate groups, forming four types: Kappa, iota, beta and lambda. Kappa comes from *kappaphycus alvarezii*, iota from *Eucheuma denticulatum*, beta from *Betaphycus gelatinane*, and lambda from *Acanthophora spicifera* (37). It is composed of alternating galactose residues, consisting of β -D-galactopyranose units linked through the 3-position and either α -D-galactopyranose or 3,6-anhydro- α -D-galactopyranose units linked through the 4-position (38). Carrageenan utilizes both its hydrophilic and anionic characteristics, with its anionic nature playing a key role in enhancing its hydrophilicity (39). *Chondrus crispus* and *Kappaphycus* species are rich sources of carrageenan, containing up to 71% and 88% of this polysaccharide, respectively - (40) .

3.3 Laminaran

Laminarin is a storage β -glucan predominantly found in brown seaweeds, such as *Laminaria/Saccharina*, *Ascophyllum*, *Fucus*, and *Undaria* species (41). Structurally, it is a β -D-(1 $\rightarrow$ 3)- linked glucan with occasional β -(1 $\rightarrow$ 6) branching. In *Ascophyllum nodosum*, laminarin has been reported to stimulate plant growth and active defense responses by inducing the production of antimicrobial phytoalexins (42). Although its large- scale commercial application remains relatively limited, notable progress has been made in France, particularly in its development as an antiviral agent in agricultural systems (43).

3.4 Fucoidans

Fucoidans are sulphated polysaccharides composed primarily of fucose, originally described by Kylin in,1913, nearly a century ago. These compounds are typically isolated from brown algal species (Phaeophyceae), particularly *Fucus vesiculosus* and *Ascophyllum nodosum* (44). It is mainly made up of sulphated L- fucose, with other monosaccharides contributing less than 10% the total composition (45). Fucoidans possess structurally diverse and highly branched polysaccharide backbones, reflecting their heterogeneous molecular architecture (46). Fucoidan is regarded as a cell

wall- strengthening compound and is believed to play a role in protecting seaweeds from desiccation stress during exposure at low tide (47).

3.5 Alginate

Alginate is another key polysaccharide sourced from brown seaweeds, particularly species of *Laminaria*, *Macrocystis*, *Sargassum*, and *Ascophyllum* (48). It occurs in both acidic and salt forms. The acidic form, known as alginic acid, is a linear polyuronic acid while the salt form is a major structural component of the brown algal cell wall, accounting for approximately 40-47% of the algal dry biomass (49). Alginates consist of β -D-mannuronate and α -L-guluronate residues that are linked together through 1,4- glycosidic bonds (50). Alginate and a range of other polysaccharides, including sulphated forms, have been identified as bioactive compounds that promote root growth through both direct effects on plants and indirect interactions with associated microorganisms (51). In addition, these polysaccharides activate plant defense responses by triggering innate immune mechanisms (52) and inducing the expression of genes associated with pathogenesis- related defense (32).

3.6. Ulva

Ulvan, originally termed ulvin and ulvacin by Kylin, refers to water-soluble sulphated polysaccharides from ulvales, mainly *Ulva* and *Enteromorpha*. It is a high negative charged sulphated polyelectrolyte composed primarily of rhamnose, uronic acids, and xylose as the principal monosaccharide units, and they characteristically contain a common disaccharide unit, the aldobiuronic acid [$\rightarrow$ 4)-D-glucuronic acid-(1 $\rightarrow$ 4)-L-rhamnose-3-sulphate (1 $\rightarrow$)] (53). Ulvan is a plant immunity activator with a strong association to the JA-pathway mechanism in experimental systems. The hormonal pathway specificity is important for disease management positioning because JA/ET- centric responses are often linked to enhanced resistance against necrotrophy and certain insect pests, whereas SA- centric responses are more often linked to biotroph/hemibiotroph resistance; in real crops, these pathways commonly interact rather than operate in isolation (54)

3.7. Lipids and Sterols

Seaweed also contains unique fatty acids, sterols, and polyunsaturated esters with antimicrobial properties. Chloroform extracts of brown and red algae rich in alcohols and esters have exhibited antibacterial activity against cotton pathogens (25).

3.8. Phlorotannins and Phenolics

Brown algae produce phlorotannins and phenolic compounds with strong antioxidant and antimicrobial activities. These compounds contribute to pathogen resistance by scavenging reactive oxygen species and reinforcing plant cell walls (24).

3.9. Phytohormones and Betaines

Seaweed extracts contain natural plant growth regulators including cytokinins, auxins, gibberellins, and betaines such as 1- aminocyclopropane -1- carboxylic acid (ACC). These compounds enhance plant vigor and stress tolerance, indirectly reducing susceptibility to nematodes and other pathogens (10, 25)

4. Secondary Metabolites

Beyond polysaccharides, phenolics and other secondary metabolites constitute a major class of bioactive compounds in seaweed, particularly in brown algae. Literature on *Ascophyllum*- based products highlights the presence of phenolic constituents, including phlorotannins, along with betaines, fatty acids, steroids, polyamines, and hormone-like compounds in brown seaweed biomass and extracts. These components, acting individually or synergistically, are implicated in plant growth modulation and enhanced disease resilience. In parallel, studies focusing on phlorotannins report broad-spectrum antimicrobial activities, including antibacterial, antifungal, and antiviral effects against a range of microbial targets. However, while these findings support the potential for direct antimicrobial activity, most agronomic disease management outcomes are more consistently attributed to the activation of host defense mechanisms rather than direct pathogen suppression under field conditions (11).

Marine seaweeds are also rich in diverse secondary metabolites with significant ecological and biological functions. For instance, GC-MS profiling of crude extract from *Sargassum cristifolium* revealed a total of 25 compounds, demonstrating substantial chemical diversity. Among these, compounds such as squalene, ethanone and phytol were predominant and are considered to contribute significantly to the observed antifungal activity (55).

Analysis of *Ulva* extract revealed that its soluble fraction primarily consisted of rhamnose, uronic acids, and sulfur, with smaller amounts of xylose, glucose, and proteins. This composition indicates the presence of the heteropolysaccharide ulvan, accounting for over 25% of the dry weight. Infrared spectra confirmed the presence of sulphate groups and exhibited the characteristic absorption bands of uronic acid and sulfated rhamnose (56) .

5. Mechanism against Plant Pathogens

5.1 Antifungal strategy

The effect of seaweed extracts on the activities of defence-related enzymes a broad spectrum of plant pathogens through both direct inhibition and induction of host defense mechanisms (Table 1). The brown sea algae *Ascophyllum nodosum* is a perennial species, has been extensively studied for its bioactive properties. Extract derived from *A.nodosum* extract (ANE) have been shown to significantly reduced the incidence and severity of foliar blights caused by *Alternaria* and

Botrytis in carrots. Moreover, ANE has been reported to enhance the expression of plant defense-related genes, including chalcone synthase, LTP, NPR-1, PR-1, PR-5, and PAL, along with enhancing the activities of defense enzymes such as POD, PPO, β -1,3- glucanase, chitinase, and PAL(11, 62). The green seaweed *Ulva lacinulata* (previously *Ulva armoricana*) is useful in lowering plant diseases. In common bean, cucumber, and grapevine plants, respectively, crude extract of *U.lacinulata* have been demonstrated to considerably lessen the severity of illness caused by three distinct powdery mildew pathogens (*Erysiphe polygoni*, *Erysiphe necator*, and *Sphaeroteca fuliginea*) (56).

According to earlier studies, algae extracts contain chemicals that biologically regulate hyphae growth and germination, increase intracellular holes (Vacuolization), and interfere with fungal cell activity (57). Seaweed extract have been widely reported to promote plant growth while exhibiting antifungal activity against soil-borne phytopathogens (58) . Organic solvent extracts, particularly methanol and ethyl acetate fractions of *U. lacinulata* have demonstrated strong antifungal activity against pathogens such as *Fusarium solani*, *Fusarium oxysporum*, *Trichoderma hamatum*, *Aspergillus flavipes*, and *Candida albicans* based on samples collected from the Mediterranean coast of Alexandria (59) . Similarly, the methanolic extract of *Codium fragile* have shown notable antifungal activity against *Alternaria alternata*, *Fusarium oxysporum*, *Alternaria brassicicola*, *Ulocladium botrytis*, and *Botryotricum piluliferum* (60). In addition, the methanolic extract of *Cystoseira myrica*, followed by *Sargassum cinereum*, exhibited strong antagonistic effects against *Fusarium oxysporum*. GC-MS analysis of these algal extracts revealed the presence of several bioactive compounds, including dimethylocta-1,6-dien-3-ol, 1-methoxy-4-(2-propenyl), hexadecenoic acid methyl ester, and octadecanoic acid methyl ester, which are likely associated with the observed antifungal activity. Infection by *F.oxysporum* reduced shoot and root dry weights and decreased photosynthetic pigments, while increasing soluble sugars and proteins but reducing their total contents (61).

Greenhouse trials showed that spraying carrot plants with a 0.2% extract of *Ascophyllum nodosum* and inoculating them 6h later with *Alternaria radicina* and *Botrytis cinerea*, followed by two additional applications at 10 and 20 days, significantly reduced disease severity at 10 and 25 days compared with water-treated controls. the seaweed extract activities of defence- related enzymes, including peroxidase, polyphenol oxidase, phenylalanine ammonia-lyase, chitinase, and β -1,3- glucanase within 12h of treatment. Treated plants also showed elevated transcript levels of PR-1, PR-5, NPR-1, chitinase, lipid transfer protein, PAL, and chalcone synthase (62).

Table 1. The table highlights the antifungal activity of seaweed extract against plant pathogenic fungi. It also indicates the related crop diseases and the reported antifungal mechanisms.

Seaweed species (Division)	Extract/ formulation	Target plant pathogenic fungi	Crop/ disease relevance	Antifungal activity	Produced antifungal mechanism	Reference
<i>Sargassum oligocystum</i> (Phaeophyta)	Dichloromethane, hexane	<i>Ganoderma boninense</i>	Oil-palm-basal stem rot	Moderate inhibition of mycelial growth in vitro; solvent-dependent activity	Lipophilic antifungal metabolites (fatty acid, terpenoids)	(63)
<i>Caulerpa racemosa</i> (chlorophyta)	Dichloromethane, hexane			Significant growth inhibition (up to ~ 33- 40%)	Membrane disruption by fatty acids and alcohols	
<i>Caulerpa racemosa</i> var. <i>lamourouxii</i> (chlorophyta)	Dichloromethane, hexane			Highest inhibition among tested species ($\approx$ 47% at 0.25 mg mL ⁻¹)	Phytol- tetradecanoic-acid-mediated antifungal action	
<i>Halimeda macrophysa</i> (chlorophyta)	Dichloromethane, hexane			Dose-dependent inhibition of fungal growth	Interference with mycelial development	
<i>Enteromorpha flexuosa</i> (chlorophyta)	Methanol, ethyl acetate	<i>Alternaria solani</i>	Tomato-early blight	Strong inhibition (Up to 94%)	Phenolic- rich extract suppresses spore germination	(64)
<i>Chaetomorpha antennina</i> (chlorophyta)	Ethyl acetate			High inhibition (~ 84%); active TLC fraction identified	Concentrate antifungal metabolites	
<i>Ulva lactuca</i> (chlorophyta)	Organic extracts			Moderate inhibition correlated with high	Antioxidant- linked antifungal activity	

				phenolic content		
Sargassum tenerrimum (Phaeophyta)	Aqueous, methanolic	Fusarium oxysporum, Macrophomina phaseolina, Rhizoctonia solani	Soil-borne diseases of vegetables	Highest inhibition among 32 species (up to 98% against f. oxysporum)	Broad-spectrum secondary metabolites	(65)
Multiple seaweeds (Chlorophyta, Phaeophyta, Rhodophyta; 32 spp.)	Aqueous, methanolic	F. oxysporum, M. phaseolina, R. solani	Broad crop range	Majority showed measurable antifungal effects; brown algae most potent	Synergistic action of polysaccharides, phenolics, fatty acids	(65)

5.2. Antiviral

Seaweed- derived polysaccharides show emerging potential against plant viral and viroid diseases. There is currently minimal use of algae for the biological control of viral plant diseases, and it is hard to say how they might combat viral infections. Elicitor chemicals found in *U. fasciata* extract either improve the immune system's ability to combat TMV (Tobacco mosaic virus) or prevent it from spreading (66) . Antiviral substances have been shown to prevent the transmission of viruses in two ways: either by directly preventing viral replication or by strengthening the host's immune system, which triggers SAR to combat the infection (67). The potent qualities of seaweed, such as their antiviral activity, have been extensively studied. Depending on their structure, molecular weight, and mode of action, each chemical exhibits a different antiviral response. Sulphated polysaccharides and polyphenols exhibit greater antiviral activity among the substances examined (68). The degree and type of sulfation, molecular weight, and monosaccharide compositions of marine sulfated polysaccharides, along with other structural polysaccharides and polyphenols, exhibit greater antiviral activity among the substances examined. The degree and type of sulfation, molecular weight, and monosaccharide compositions of marine sulfated polysaccharides, along with other structural features like the three- dimensional structure and hydrogen bonds, all play a significant role in the antiviral activity (69). Laminarin treatments reduced tobacco mosaic virus replication by activating host defense pathways (32). Carrageenans applied to tomato plants alleviated Tomato chlorotic dwarf viroid symptoms (32). Oligo- carrageenan sprays induced long term antiviral resistance and enhanced PAL activity in tobacco (22). These compounds act in a vaccine like manner by blocking viral entry and activating systemic defense responses (68).

5.3. Antibacterial

Seaweed extracts have shown strong antibacterial potential against several economically important plant pathogens, acting both through direct antimicrobial activity and by stimulating plant immune responses (Table 2). Their ability to activate defense- related enzymes and signaling pathways highlights seaweed-based formulations as promising, eco-friendly alternatives for managing bacterial diseases in crops (Fig. 2). The species, *Polysiphonia lanosa*, demonstrated the highest level of activity, particularly through its methanolic extract, which produced a prominent inhibition zone of 15.83 ± 0.41 mm against *Xanthomonas arboricola*. Overall, the extract exhibited storage effects on gram negative bacterial compared to Gram-positive ones (70). The methanol extract of *P. lanosa* contains promising antibacterial constituents capable of managing this destructive phytopathogen, potentially offering environmentally friendly alternatives to traditional copper-based treatment. The seaweed displayed a wide range of antimicrobial activity, except for *Ulva lactuca*, which showed no inhibitory effect against any of the tested bacterial strains (70). In addition, foliar application of seaweed extract (SWE) at a 0.5% concentration significantly reduced disease severity caused by *Xanthomonas campestris* pv. *vesicatoria* and *Alternaria solani* in tomato and sweet pepper under both greenhouse and field conditions (10). Extract of *Ascophyllum* when applied to the root of *Arabidopsis thaliana* protects *Pseudomonas syringae* pv. *tomato*. Root application of *Ascophyllum nodosum* extract (ANE and its fractions) reduced disease symptoms in *Arabidopsis* and induced resistance even in salicylic acid-deficient mutants, but not in the jar 1 (Jasmonic acid resistance 1) line. The induced resistance against *P. syringae* was mainly associated with increased expression of jasmonic acid marker PDF 1.2, while PR1 and ICS1 were less affected. ANE also protected plants from *Sclerotinia sclerotiorum*, indicating that resistance triggered by *A.nodosum* is largely jasmonic acid dependent (52). Foliar application of seaweed extracts increased chitinase, peroxidase, polyphenol oxidase, phenylalanine ammonia-lyase, and β -glucanase activities and total phenolic compounds in tomato and sweet pepper. It also upregulated SA, JA, and ET-related marker genes, leading to reduced diseases caused by *A. solani* and *Xanthomonas. campestris* pv. *vesicatoria*. These effects are attributed to active polysaccharides in the extracts that act as elicitors and induce PR proteins (71). A bioactive sulphoglycerolipid, 1-O- palmitoyl-3-O-(6'-sulpho- α -quinirovopyranosyl)- glycerol, isolated from the methanolic extract of the brown macroalgae *Sargassum wightii*, demonstrated significant antibacterial activity against *Xanthomonas oryzae* pv. *oryzae*, the causative agent of bacterial blight in rice, highlighting the potential of brown seaweed- derived lipids in plant management (72). Commercial formulations based on *Sargassum wightii* improved resistance to bacterial leaf blight in cotton by enhancing peroxidase and phenolic activity (73). Similarly, *Ascophyllum* and *Sargassum* extracts reduced bacterial spot severity in tomato and pepper crops (25).

Table 2. Antibacterial effects of seaweed extract on plant pathogens.

Seaweed (Division)	Extract/Formulation	Crop	Target plant pathogen	Antibacterial activity	Mechanism	Reference
Polysiphonia lanosa (Rhodophyta)	Methanol extract	Stone fruit & strawberry	Xanthomonas arboricola pv. pruni; X. fragariae	Inhibition zone≈15.8mm against MIC=6.25 mg/mL against X.fragariae	Not specifically reported (Broad- spectrum Gram-negative activity)	(70)
Laminaria japonica (Phaeophyta)	Petroleum-ether fraction (Fr.3)	Potato	Clavibacter michiganensis subsp. sepedonicum	Strong inhibition; MIC= 0.04mg/mL against C. michiganensis	Damages bacterial cell wall and membrane, induces ROS disrupts metabolites (glycolysis/TCA), and inhibits macromolecular synthesis	(74)
Laminaria digitata (Phaeophyta)	Methanol extract	Tomato	Agrobacterium tumefaciens	Very effective growth inhibition (Strong suppression of A. tumefaciens invitro)	Attributed to the high content of phenolic compounds and pigments that disrupt bacterial growth	(75)
Sargassum wightii (Phaeophyta)	Sulfonoglycolipid (lipid) extract	Rice	Xanthomonas oryzae pv. oryzae	Notable inhibition of X.oryzae (antibacterial activity observed)	Likely due to lipophilic fatty-acid derivatives (Sulfonoglycolipids) that disrupt gram-negative bacteria	(76)

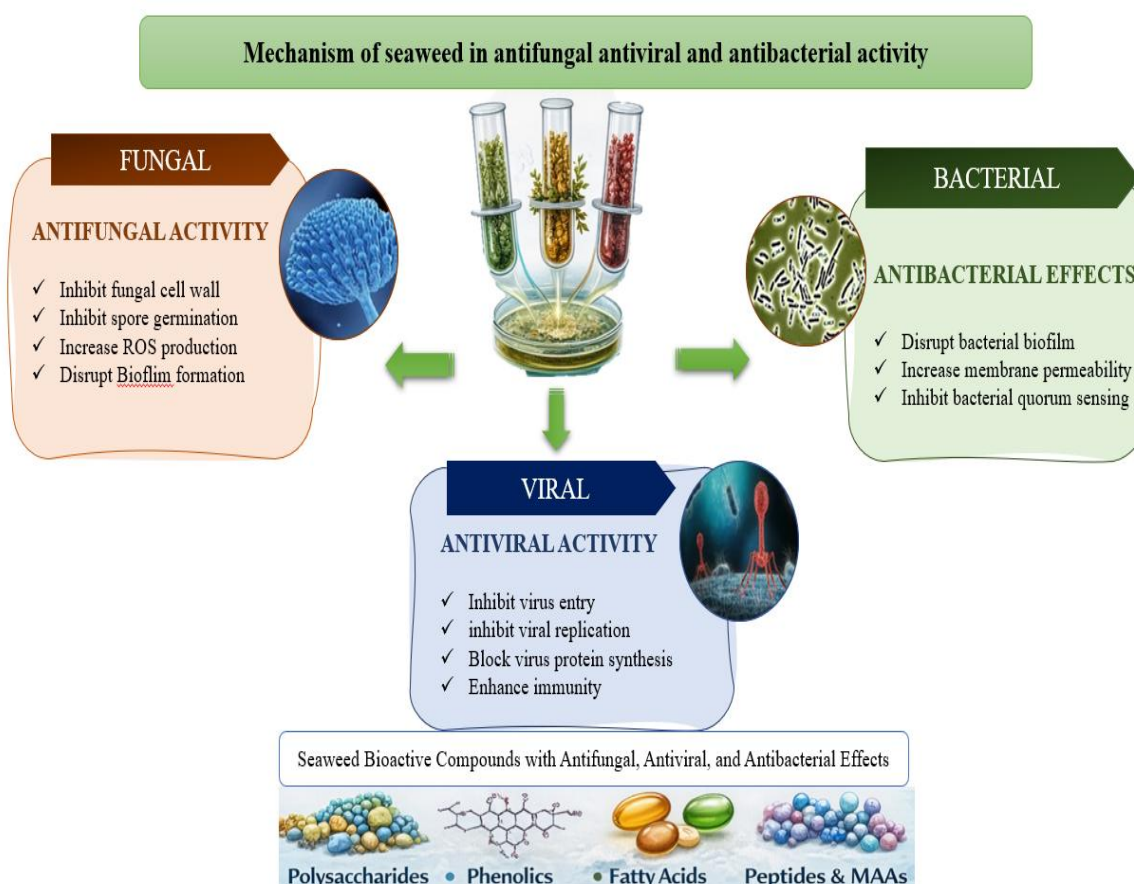


Fig. 2. A schematic illustration depicting the mechanism by which seaweed-derived compounds exert antifungal, antiviral, and antibacterial effects.

Collectively, the evidence indicates that seaweed- derived diseases suppression operates through two overlapping but distinguishable routes; direct antimicrobial effects and indirect activation or priming of plant defense. Their relative contribution depends on seaweed species, extraction method, chemical fraction, crop- pathogen combination, dose and

application route. Consequently, strong in- vitro inhibition should not automatically be interpreted as equivalent field efficacy. Polysaccharide- rich preparation may be particularly relevant to defense priming, whereas selected phenolic-, lipid- or other secondary- metabolite- rich fractions may contribute more directly to pathogen inhibition. This distinction is important when selecting seaweed extract for specific disease- management objectives.

6. Nano formulation

A recent study examined the nematocidal activity of extract from the marine algae *Colpomenia sinuosa* and *Corallina mediterranea* and the silver nanoparticles synthesized from them against *Meloidogyne incognita* infecting tomato plants. SEM and TEM analyses confirmed the anisotropic silver nano particles with size below 40nm, while FT-IR showed a sharp absorbances between 440-4000⁻¹. Among the tested samples, *C.sinuosa* derived nanoparticles showed the strongest activity by greatly reducing galls, egg masses, and egg per mass simultaneously enhancing plant growth. The methylene chloride extract of *C. sinuosa* was also more effective than that of *C. mediterranea*, particularly the third chromatographic fraction obtained with hexane: methylene chloride: ethyl acetate, which caused up to 100% mortality and contained seven bioactive compounds. Overall, *C. sinuosa*- based silver nanoparticles demonstrate strong potential as eco- friendly alternatives to synthetic nematocides (77). Similarly, silver nanoparticles synthesized from *Ulva lactuca* ethyl acetate extract showed a crystalline structure with XRD peaks at 111,200,220 and 331 planes. FTIR analysis indicated that terpenoids acted as reducing agents and palmitic acid served as a stabilizer. The spherical Ag NPs (3-50 nm), confirmed as elemental silver by EDX, exhibited strong inhibitory activity against *Fusarium oxysporum* f.sp. *vasinfectum* (MIC 80 µg mL⁻¹) and *Xanthomonas campestris* pv. *malvacearum* (MIC 43.33 µg mL⁻¹), demonstrating their potential for managing major cotton pathogens (78). In another study, Polysaccharides isolated from *Gracilaria Salicornia* were purified by DEAE- cellulose chromatography and used to synthesize nanoparticles through the addition of sodium carbonate and poly-L-lysine. FTIR and ¹H NMR analyses identified the polysaccharide as sulphated galactan. The resulting nanoparticles (GNPs) showed high stability with a zeta potential of -41 mV, were spherical and well dispersed with sizes of 20-50 nm as observed by HRTEM, and exhibited an amorphous nature based on XRD analysis. Application of GNPs enhanced tomato seedling vigor and demonstrated in vitro antifungal activity against *Alternaria solani* and *Fusarium oxysporum*. At a concentration of 100 µg, GNPs exhibited strong antifungal efficacy against the tested phytopathogenic fungi under in vitro conditions. The highest inhibition (89%) was observed against *Alternaria solani*, followed by *Fusarium oxysporum* (82%), indicating their potential as an eco-friendly control strategy for soil-borne fungal pathogens in tomato (79). In addition, Chitosan-carrageenan biopolymeric nanocomposites encapsulating mancozeb (nano CSCRG-M) were synthesized using a green chemistry approach, producing nanoparticles of 66.6-231.82 nm. The nano formulation was characterized using particle size analysis, SEM, FTIR, TEM, DSC, and TGA, with TEM revealing clover leaf-shaped particles (248.23 nm) containing both encapsulated and surface-associated fungicide. Nano CSCRG- 1.5 showed 83.1% inhibition of *Alternaria solani* at 1.5 ppm in vitro, comparable to commercial mancozeb, and achieved complete suppression of *Sclerotinia sclerotiorum* at 1.0-1.5 ppm. In pot experiments, the nanoparticles provided higher disease control efficacy (79.4± 1.1%) and improved plant growth parameters. Additionally, the nano formulation also exhibited lower cytotoxicity in Vero cells and sustainable fungicide release for up to 10 h, highlighting its potential as a safer and more sustainable environmentally safer alternative to chemical pesticides (38).

7. Commercial formulation

Commercial formulations of seaweed extract, particularly those derived from *Ascophyllum nodosum*, have gained considerable attention as eco-friendly tools for plant disease management due to their broad-spectrum activity against fungal and bacterial pathogens (Table 3). These products primarily suppress plant diseases by activating host defense mechanisms and, in some cases, through direct antimicrobial effects, highlighting their potential role in sustainable and integrated plant protection strategies. Stimplex™, an *Ascophyllum nodosum*-based seaweed extract, effectively suppressed major fungal diseases of cucumber under greenhouse conditions. Foliar and/or root drench application at a concentration of 0.5-1%, applied twice at 10-day intervals, significantly reduced disease caused by *Alternaria cucumerinum*, *Fusarium oxysporum*, *Didymella applanata*, and *Botrytis cinerea*, with the strongest effects against *Alternaria* and *Fusarium*. Combined foliar and root applications were more effective than single applications, and alternating Stimplex™ with chlorothalonil provided maximum disease reduction. Enhanced activities and expression of defense-related enzymes, along with increased phenolic accumulation, indicate that disease control is mediated through the induction of host defense responses (80). In greenhouse studies on cucumber, Marmarine significantly reduced damping off caused by *Phytophthora melonis* and enhanced the plant's overall defense response against the pathogen. The disease-suppressive activity is mainly attributed to the elicitor properties of carbohydrate components, particularly oligosaccharides and polysaccharides, present in the formulation (81). Marmarine can be applied via foliar spray, root drench, or soil drench; however, foliar application is generally more effective than root application, likely due to greater availability and mobility of elicitor molecules when applied as a spray. The commercial liquid seaweed extract (Seasol™), derived from *Durvillaea potatorum* and *Ascophyllum nodosum*, significantly suppressed clubroot disease in broccoli caused by *Plasmodiophora brassicae* using a sand culture system. The extract (16% w/w soluble solids), applied at dilutions of 1:25 and 1:200, reduced primary and secondary infections by up to 55% and 84%, respectively, at 45 days after inoculation (82). Root infection was assessed at 14-, 28-, and 45-days post inoculation using FFA phloxine B staining techniques. Although the extract mechanism is unknown, activation of plant defence responses and/or natural growth regulators was suggested, marking the first report of direct suppression of *P. brassicae* infection in broccoli by a seaweed extract. A commercial seaweed extract (Seasol™) derived from *Durvillaea potatorum* and *Ascophyllum nodosum* directly suppressed *Sclerotinia minor* using in vitro bioassays. The undiluted extract inhibited mycelial growth

by 18-100 % and suppressed sclerotial growth by 90%, while a 1:500 dilution reduced sclerotial growth by 30% and lowered disease severity in lettuce seedlings. In contrast, pH-buffered controls suppressed sclerotia by only 22% and 0%. This study concluded that disease suppression was only partly due to alkaline pH, with other organic compounds likely responsible for the main antifungal effect. An Australian field study further demonstrated reduced incidence of white blister disease caused by *Albugo candida* in broccoli following treatment with a commercial seaweed extract (Seasol™) (83). A randomized complete block design with four replicates was used, applying the extract at 2.5 or 25L ha⁻¹, with water as the control. In addition, Broccoli seedlings were soaked overnight in a diluted extract (1: 200 v/v), transplanted, and subsequently received three soil drenches at 0, 10, and 20 days. Disease incidence, assessed as the number of leaves per plant containing at least one pustule, was reduced by 23% ($p \leq 0.05$) during the establishment stage, irrespective of application rate. Although the mechanism remains unknown, this study represents the first report of a seaweed extract reducing white blister incidence in broccoli and supports earlier findings of disease suppression by *Ascophyllum nodosum* extract against several foliar pathogens in other vegetable crops (83). In addition, an *Ascophyllum nodosum*- based formulation, a commercial brown seaweed-derived extract, Stella maris exhibited strong elicitor activity in *Arabidopsis thaliana*. At low concentration (0.05%), it significantly induced GUS expression in CYP71A12 pro: GUS lines, indicating activation of innate immune responses, and enhanced ROS-mediated defense through increased hydrogen peroxide production. The extract upregulated key defense- related genes, including CYP71A12, PR-1, and WRKY30. At higher concentration (20-50%), Stella Maris™ showed direct antibacterial activity against *Pseudomonas syringae*, *Pseudomonas aeruginosa*, and *Xanthomonas campestris*. Treatment reduced bacterial growth by 20-41% in growth media and lowered pathogen loads in plant tissues, with the highest protection observed against *P. syringae* (84). Dravya™, a commercial aqueous seaweed extract, effectively reduced bacterial blight of cotton caused by *Xanthomonas campestris* pv. *malvacearum*. Seed treatment (1:500) followed by three foliar sprays at 10-day intervals reduced disease incidence by 66-74% between 40 and 80 days after sowing. This induced systemic resistance was associated with improved growth parameter yield traits, chlorophyll content and enhanced level of phenolics, and peroxidase activity, highlighting Dravya™ as an eco-friendly option for integrated bacterial disease management (73).

Table 3. Commercial seaweed- based formulations for plant diseases management. Sources, target, and applications.

Seaweed	Commercial formulation	Crop	Pathogen	Reference
<i>Ascophyllum nodosum</i>	Stimplex™	Cucumber	<i>Alternaria cucumerinum</i> , <i>Fusarium oxysporum</i> , <i>Botrytis cinerea</i> , <i>Didymella applanata</i> .	(80)
<i>Ascophyllum nodosum</i>	Dalgin	Tomato	<i>Phytophthora capsica</i>	(85)
<i>D. potatorum</i> and <i>A. nodosum</i>	Seasol™	Broccoli	<i>Plasmodiophora brassicae</i>	(82)
<i>D. potatorum</i> and <i>A. nodosum</i>	Seasol™	Lettuce	<i>Sclerotinia minor</i>	(83)
<i>Ascophyllum nodosum</i>	Stella Maris	Calibrachoa leaf	<i>Aspergillus flavus</i> , <i>Candida albicans</i> , <i>Penicillium funiculosum</i> , and <i>Penicillium ochrochloron</i>	(86)
Seaweed	<i>Kappaphycus alvarezii</i>	Tomato	<i>Fusarium oxysporum</i> f.sp. <i>lycopersici</i>	(87)
Commercial formulation	<i>K. alvarezii</i> + <i>Sargassum</i> sp.	Tomato	<i>Fusarium oxysporum</i> f.sp. <i>lycopersici</i>	(87)
<i>Sargassum wightii</i>	Dravya	Cotton	<i>Xanthomonas campestris</i> pv. <i>malvacearum</i>	(73)

8. Bioformulation Design and Delivery Systems

In practical crop protection, the effectiveness of disease management depends on delivery as much as chemistry. Seaweed-based disease- management inputs therefore benefit from explicit formulation engineering to improve stability, adherence, rain fastness, spatiotemporal release and compatibility with tank mixes or microbial partners. This “bioformulation” framing is strongly developed in the microbial- biologicals literature, where long- term viability, UV resistance, and controlled release are core constraints for field success and product registration (88)

Application route shapes outcomes, Seaweed extract literature emphasizes foliar spray, root and soil application, or combined programmes such as fertigation, drenching, dripping, and notes that foliar absorption can be rapid, while soil adsorption can limit immediate mobility. This is relevant in disease management because foliar sprays target phyllosphere defense priming against foliar pathogens, whereas soil/root applications may be more relevant for root pathogens, nematodes, and rhizosphere-mediated ISR effects (10). A recurring practical theme is that seaweed extracts are active at low doses and often applied repeatedly as part of a programme rather than as single “curative” sprays. For example, seaweed extract reviews cite low-concentration foliar spray being associated with effective disease control and yield outcomes, and also discuss application intervals on the order of 10–14 days for optimal plant responses in some systems. This repeated application logic is consistent with priming biology, where the primed state can be transient and may need reinduction depending on crop growth rate and pathogen pressure (10).

Encapsulation performance is tunable: systematic reviews of microbial encapsulation report common parameter regimes such as sodium alginate at 1–3%, and CaCl_2 crosslinkers 1–2% with additives (Starch, bentonite, gelatin, etc.) used to modify bead structure, porosity, biodegradation, and microbial survival. Seaweed-based plant disease management can leverage this as a design space for deploying microbial biocontrol agents (BCAs) more reliably in soil or on seed, roots, especially under heat, UV and desiccation stress (89). Seaweed bioformulation may also involve co-formulation or co-application with other elicitors/bio-stimulants. A representative example is the synergistic activation of host defense when *Ascophyllum* extract is combined with chitosan, showing that “bioformulation” can be conceptualized as a designed elicitor mixture rather than a single active fraction. Such combinations are mechanistically plausible because multiple elicitors can converge on overlapping defense nodes like ROS, PR proteins, and phenylpropanoid enzymes while engaging different upstream receptors or signaling crosstalk (90).

An emerging area of interest is nano- and micro-structured delivery development of systems such as nano-encapsulated botanicals/microbial bio stimulants; liposomes; hydrogel matrices. While much of this field is not yet seaweed-specific, alginate- and carrageenan-based hydrogels/ nano-constructs are increasingly discussed as scalable bio-based delivery platforms. For seaweed-based disease management, the key translation barrier is not only efficacy but also clear safety and environmental fate characterization, because any new particulate delivery system can provide non-target and regulatory scrutiny (91).

Formulation should therefore be considered a translation bridge between seaweed chemistry and field disease-management performance, rather than simply a downstream processing step. Stability, retention, release, dose efficiency and compatibility with microbial or other crop-protection inputs, can determine whether laboratory activity becomes practical field efficacy. This formulation-centered perspective distinguishes the present reviews focused primarily on seaweed bioactivity, biostimulation or elicitation.

9. Synergistic effect

The combined application of seaweed extracts with chemical fungicides, biocontrol agents, and natural elicitors has emerged as a promising strategy for enhancing disease suppression while reducing reliance on synthetic inputs. Such combinations not only improve pathogen suppression but also strengthen plant innate defense responses, resulting in improved crop health and resilience against multiple diseases. Dravya, a seaweed-based extract, has been evaluated as a seed treatment along with fungicides for the management of *Alternaria padwickii* and *Bipolaris oryzae* in rice. It was highly compatible with Bavistin and Dithane M-45 and significantly reduced *A. padwickii* and *Bipolaris oryzae* incidence. Dravya also improved seed germination and seedling vigour and enhanced peroxidase activity, which was about twofold higher than the control. Reduced disease incidence under greenhouse conditions indicates the promising efficacy of Dravya in combination with Dithane M-45 (92). Similarly, the application of seaweed alone or in combination with Topsin-M and carbofuran effectively suppressed root-rot pathogens. In tomato these treatment reduced infections caused by *Rhizoctonia solani* and *Fusarium solani*. Under field conditions sunflower plants treated with seaweed extract alone or in combination with these pesticides significantly decreased root-rot incidence by limiting infections of *Macrophomina phaseolina*, *F. solani*, and *R. solani* (93). The combined use of ANE (*Ascophyllum nodosum* extract) and CHT (Chitosan) markedly inhibited pathogen development, reducing disease severity to 35% compared with 90.5% in the control. This treatment enhanced plant defense responses by increasing the activities of phenylalanine ammonia lyase and peroxidase, along with elevated production of reactive oxygen species and hydrogen peroxide. It also upregulated defense-related genes associated with jasmonic acid signaling (LOX1, CO1), salicylic acid-mediated pathways (NPR1, PR1), and other defense mechanisms, including NADPH oxidase and C4H (94). Furthermore, the red alga *Soliera robusta*, when used in combination with *Pseudomonas aeruginosa*, exhibited enhanced effectiveness in controlling *Fusarium solani* infection (95).

10. Challenges & Future perspectives

The composition and efficacy of seaweed extracts can vary widely depending on species, location, season, harvest time, and processing methods, which leads to inconsistent disease performance control (96). Seaweed products often act preventively rather than curatively, which may not meet farmers’ needs for rapid diseases suppression. Formulation stability is another impediment as many bioactive compounds degrade under UV, heat or oxidation, so developing affordable, long-shelf-life products is difficult (97). Regulatory ambiguity adds complexity, since seaweed extracts can be classified as fertilizers, bio stimulants or biopesticides depending on different regions (96). Technical barriers also persist in extracting seaweed proteins/ peptides, because rigid algal cell walls, strong polysaccharides binding and possible antinutritional or toxic compounds hamper purification; moreover, higher extract doses do not necessarily improve control and can even harm plants (98).

Despite these limitations, seaweed extract holds strong future promise as multifunctional biocontrol agents: many contain polysaccharide elicitors (laminarin, carrageenans, ulvans and fucoidans) that activate plant immune pathways (SAR/ISR) against fungal, bacterial and viral pathogens (22,10). With tighter restrictions on synthetic pesticides and rising demand for residue-free food, seaweed bio stimulants are expected to become integral to integrated disease management and organic systems (96). Emerging formulation technologies (nano- encapsulation, emulsions and controlled-release carriers) may improve the bioactive compounds under field conditions (97). Combining seaweed extracts with beneficial microbes (e.g. *Bacillus*, *Trichoderma*) has shown synergistic disease suppression, and studies suggest seaweed treatments can also reshape the rhizosphere microbiome to favour beneficial, pathogens-suppressive microbes (25). Supportive regulatory frame were such as the EU Fertilizing products regulation along with deeper mechanistic research are likely to accelerate adoption overall, seaweed products already enhance crop growth, yield and stress tolerance (99).

11. CONCLUSION

Seaweed-derived bioformulations have emerged as an effective and sustainable alternative to conventional chemical pesticides, addressing major concerns such as environmental pollution, development of pathogen resistance, and negative impacts on beneficial organisms. Marine macroalgae, including green, brown, and red seaweeds, are rich sources of bioactive compounds such as polysaccharides, phenolics, and phytohormones that play a crucial role in enhancing plant health. Major polysaccharides like laminarin, carrageenan, fucoidan, alginate, and ulvan function as potent elicitors of plant defence responses by activating systemic acquired resistance (SAR) and induced systemic resistance (ISR) pathways. In addition to stimulating host immunity, seaweed extracts also demonstrate direct antifungal, antibacterial, and antiviral activities against a wide range of economically important plant pathogens. Recent technological advances in extraction methods and the development of nano-formulations have further increased the stability, bioavailability, and field efficiency of seaweed-based products. Moreover, seaweed-based inputs contribute to improved soil fertility and support beneficial microbial communities, thereby promoting overall agroecosystem health and sustainability. With growing global production of seaweed biomass and increasing commercialization of seaweed-derived products, their integration into Modern crop protection strategies is becoming more feasible. However, regulatory frameworks continue to evolve, emphasizing the need for standardization, quality control, and scientific validation of efficacy. Overall, seaweed-based bioformulations hold immense potential for integrated disease management, sustainable crop production, and enhancing resilience in agricultural systems, ultimately contributing to global food security. This major research priority is therefore not to further demonstrate that seaweed extract possess biological activity, but to establish which seaweed- bioactive- formulation combinations provide reproducible, dose-optimized, field- validated, economically safe disease suppression.

CRedit Authorship contribution statement

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