

Review article

Phytochemical Composition, Biological Potential, and Future Applications of Sargassum Species: A Review

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Abstract

This comprehensive review examines the phytochemical composition and bioactive properties of *Sargassum* species, with emphasis on extraction methodologies, analytical techniques, and biological activities. The genus *Sargassum* harbors a diverse array of bioactive compounds, including polyphenols, flavonoids, fucoidans, terpenes, and various secondary metabolites across multiple species. Their potential applications span pharmaceutical, cosmeceutical, and agricultural industries. This review critically evaluates the analytical approaches employed for compound identification and characterization, highlighting the considerable potential of different *Sargassum* species and their derivatives for the development of novel therapeutic agents with antimicrobial, antioxidant, anti-inflammatory, antitumor, and antidiabetic activities. Current challenges and future research directions are discussed to facilitate the commercialization of these marine resources.

Keywords: bioactive compounds; biological activities; extraction methods; marine natural products; *Sargassum*

1. Introduction

Brown macroalgae belonging to the genus *Sargassum* (Phaeophyceae) represent a valuable resource for bioactive compound discovery, demonstrating substantial potential in healthcare and industrial applications (Pamungkas et al., 2024; Zhang et al., 2024). The phytochemical constituents of these marine organisms confer diverse biological benefits, positioning them as promising candidates for natural product-based therapeutics and alternatives to conventional synthetic compounds (Schwartz et al., 2017; Lim et al., 2023b). Research investigating *Sargassum* extracts has expanded considerably in recent years, elucidating optimal extraction methodologies and characterization techniques for bioactive compounds. The genus comprises approximately 350 species distributed throughout tropical and temperate marine ecosystems, with several species demonstrating remarkable adaptability to diverse environmental conditions and exhibiting distinct phytochemical profiles that reflect their ecological niches (Anburaj et al., 2024).

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Macroalgae, particularly *Sargassum* species, constitute a rich reservoir of structurally diverse bioactive compounds exhibiting multiple biological activities. These brown seaweeds synthesize an extensive array of phytochemicals, together with polyphenols, terpenes, alkaloids, flavonoids, and polysaccharides, which collectively contribute to their therapeutic properties (Senthilkumar et al., 2024). Comprehensive phytochemical analysis of these organisms is essential for understanding their potential applications across pharmaceutical, cosmeceutical, food additive, and agricultural sectors. The biosynthesis of these secondary metabolites is influenced by various environmental factors, such as salinity, temperature, light intensity, and nutrient availability, resulting in substantial intraspecific and interspecific variation in compound composition and concentration.

The growing global demand for natural products, along with increasing concerns over the adverse effects and environmental impact of synthetic chemicals, has intensified research into marine-derived bioactive compounds. *Sargassum* species have emerged as particularly attractive candidates due to their abundance, rapid growth rates, and capacity to produce unique chemical structures not commonly found in terrestrial organisms (Robledo et al., 2021). Moreover, the sustainable harvesting of *Sargassum* biomass presents economic opportunities for coastal communities while simultaneously addressing environmental challenges associated with excessive algal blooms in certain geographical regions (Martínez-Martínez et al., 2025). The development of value-added products from *Sargassum* aligns with principles of the blue economy and marine resource sustainability, offering potential solutions to both resource utilization and environmental management (Adharini et al., 2025).

Recent advances in analytical technologies, together with high-resolution mass spectrometry, nuclear magnetic resonance spectroscopy, and sophisticated chromatographic techniques, have facilitated unprecedented insight into the chemical complexity of *Sargassum* metabolomes. These technological developments have enabled researchers to identify novel compounds with unique structural features and biological activities, thereby expanding the chemical space available for drug discovery and industrial applications (Thomford et al., 2018). Moreover, integration of metabolomics approaches with traditional phytochemical analysis has revealed intricate relationships between chemical composition and biological activity, enhancing our understanding of structure-activity relationships and facilitating rational design of bioactive formulations (Latif & Nawaz, 2025). Despite the substantial progress in *Sargassum* phytochemistry research, several challenges persist that limit the translation of laboratory findings into commercial applications. These include variability in phytochemical composition due to seasonal and geographical factors, lack of standardization in extraction and analytical protocols, limited understanding of pharmacokinetic properties and bioavailability of marine-derived compounds, and regulatory considerations for commercialization of novel marine natural products (Kumari et al., 2025). Additionally, the ecological implications of large-scale *Sargassum* harvesting require careful evaluation to ensure sustainable resource management and preservation of marine biodiversity.

This review synthesizes current knowledge regarding the phytochemical composition of various *Sargassum* species, emphasizing extraction and analytical methodologies, identified compounds, and their associated biological activities. By examining the diverse range of compounds in these seaweeds, this review aims to elucidate their potential applications across multiple industries while identifying key research gaps that require further investigation. Particular attention is devoted to evaluating the therapeutic potential of *Sargassum*-derived compounds in addressing contemporary health challenges, together with antimicrobial resistance, oxidative stress-related diseases,

metabolic disorders, and cancer. This review discusses emerging applications in agriculture and environmental remediation, highlighting the multifaceted utility of *Sargassum* as a sustainable biological resource for the 21st century.

2. Phytochemical Composition of *Sargassum* Species

2.1 Major phytochemical classes

Sargassum, a taxonomically diverse genus of brown macroalgae, contains abundant phytochemicals that contribute significantly to its biological activities and potential applications in medicine, cosmetics, and the food industry (Schwartz et al., 2017; Haron et al., 2022). The primary phytochemical classes identified in *Sargassum* include phenolic compounds, polysaccharides, and terpenoids, each exhibiting distinct roles in the organism's ecological and biochemical properties (El-Baroty et al., 2024). Phenolic compounds, particularly phlorotannins, are abundant in *Sargassum* and contribute substantially to its antioxidant capacity (Palanisamy et al., 2018). Phlorotannins are polyphenols unique to brown algae that confer protection against oxidative stress and ultraviolet radiation. These compounds also exhibit antimicrobial and antitumor activities (Ningsih et al., 2020), rendering them promising candidates for therapeutic applications (Morales et al., 2006; Dewinta et al., 2023). Additionally, these compounds function in *Sargassum*'s defense mechanisms, protecting against herbivory and environmental stressors. Various *Sargassum* species have been documented to contain multiple phytochemical classes, as summarized in Table 1. These include phenolics, flavonoids, alkaloids, terpenoids, pigments, polysaccharides, sterols, and tannins.

Table 1. Major phytochemical classes identified in *Sargassum* species

Phytochemical Class	Specific Compounds	<i>Sargassum</i> Species	Reference
Phenolics	Phenolic acids, Phlorotannins	<i>S. polycystum</i> , <i>S. wightii</i>	(Unnikrishnan et al., 2015; Zhao et al., 2023)
Flavonoids	Ephedrannin A, Hinokiflavone	<i>S. polycystum</i> , <i>S. wightii</i>	(Haron et al., 2022; Senthilkumar et al., 2024)
Alkaloids	Various alkaloids	<i>S. polycystum</i> , <i>S. wightii</i>	(Unnikrishnan et al., 2015; Pamungkas et al., 2024)
Terpenoids	Various terpenoids	<i>S. muticum</i>	(Schwartz et al., 2017; Pamungkas et al., 2024)
Pigments	Fucoxanthin, Chlorophyll a, b	<i>S. polycystum</i> , <i>S. latifolium</i>	(Ahmed et al. 2024: Senthilkumar et al., 2024)
Polysaccharides	Alginates, Fucoidans, Sulfated polysaccharides	<i>S. fusiforme</i> , <i>S. euryphyllum</i> , <i>S. aquifolium</i>	(Ismail et al., 2022; Zhang et al., 2024)
Sterols	Various sterols	<i>S. aquifolium</i>	(Moni et al., 2021; Ahmed et al., 2024)
Tannins	Various tannins	<i>S. latifolium</i> , <i>S. wightii</i>	(Rajivgandhi et al., 2021; Ahmed et al., 2024)

The phytochemical diversity of *Sargassum* species reflects the wide range of bioactive compounds reported across different taxa (Table 1). Each phytochemical class includes compounds identified in multiple species, with *S. polycystum* and *S. wightii* most frequently reported, reflecting their rich phytochemical diversity. Phenolics, flavonoids, and alkaloids are predominantly identified in these species, while other classes, such as polysaccharides and sterols, are characteristic of distinct species as well as *S. fusiforme* and *S. aquifolium* (Haron et al., 2022; Ismail et al., 2022). The data in Table 1 also highlights the presence of pigments such as fucoxanthin and chlorophylls in *S. polycystum* and *S. latifolium*. Fucoxanthin is a well-characterized carotenoid (Zandi et al., 2010). Additionally, the presence of polysaccharides, plus alginates and fucoidans was found in *S. fusiforme*, *S. euryphyllum*, and *S. aquifolium*. Table 1 underscores the importance of ongoing research in this field, as reflected in studies published between 2015 and 2024. The increasing number of recent publications reflects growing interest in exploring the biotechnological potential of *Sargassum* species (Jayasinghe et al., 2023).

Figure 1 illustrates the distribution of phytochemical classes in *Sargassum*, highlighting the relative abundance of various bioactive compounds. Phenolic compounds constitute the highest proportion (25%). Flavonoids, another important polyphenol class, comprise 18% of the composition. Alkaloids, representing 12%, are bioactive nitrogen-containing compounds frequently found. Terpenoids account for 10%. Polysaccharides constitute 20% of the composition, representing crucial structural and functional biomolecules in *Sargassum*. The remaining 15% comprises the "Others" category, which are potentially sterols, proteins, and additional secondary metabolites. This diverse phytochemical composition highlights *Sargassum*'s potential as a valuable resource for pharmaceutical and nutraceutical applications.

The comparative analysis of total phenolic content across various *Sargassum* species shows clear variation in phenolic levels, which correlate strongly with antioxidant capacity, as depicted in Figure 1. Phenolic content is strongly correlated with antioxidant activity as these compounds neutralize free radicals and mitigate oxidative stress. According to the data, *S. aquifolium* exhibits the highest total phenolic content (87.2 mg GAE/g), followed by *S. wightii* (45.0 mg GAE/g) and *S. muticum* (30.0 mg GAE/g) (Table 2). Conversely, *S. filipendula* and *S. latifolium* demonstrate lower phenolic contents of 10.0 mg GAE/g and 4.3 mg GAE/g, respectively. These data indicate that species with elevated phenolic content, such as *S. aquifolium* and *S. wightii*, likely possess stronger antioxidant activity compared to other species. Phenolic compounds in *Sargassum* inhibit lipid peroxidation, protect cells from oxidative damage, and potentially confer health benefits as well as anti-inflammatory and anti-aging effects. Consequently, species with high phenolic content represent promising natural antioxidant sources for pharmaceutical, cosmetic, and functional food applications (Panzella, 2020; Dias et al., 2021). Variation in phenolic content among *Sargassum* species may result from differences in habitat, geographic conditions, and extraction methods. Species with lower phenolic levels may still possess other bioactive properties, meriting further investigation.

2.2 Quantitative analysis of key compounds

Multiple studies have quantified major bioactive compounds in *Sargassum* species, revealing significant variations depending on species, extraction methodology, and analytical technique employed. Representative examples are provided in Figure 2. Figure 2 illustrates various analytical techniques employed in the phytochemical analysis of

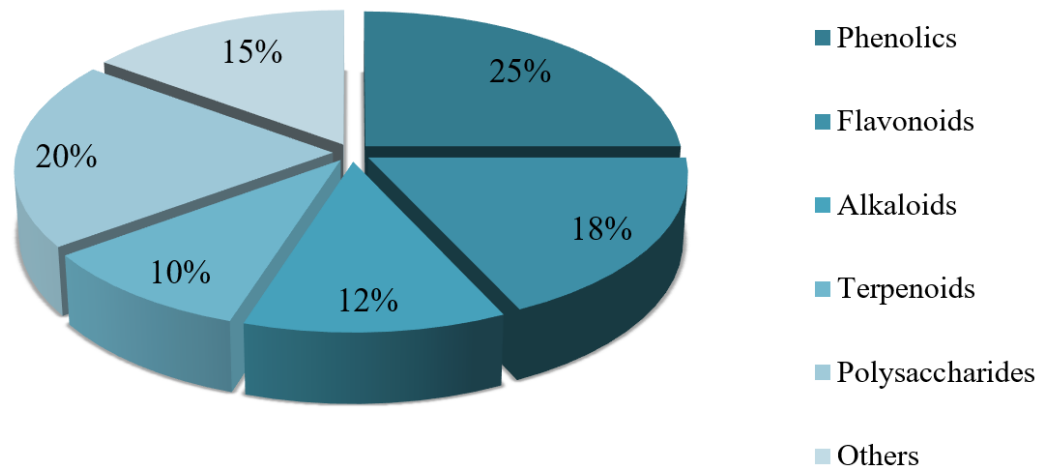


Figure 1. Major phytochemical variation in *Sargassum* species

Table 2. Total phenolic content in *Sargassum* species

Species	Extraction Solvent	Extraction Method	Extraction Conditions	Total Phenolic Content (mg GAE/g)	Reference
<i>S. aquifolium</i>	Methanol 80%	Maceration	Room temp; 24h; 1:20 (w/v)	87.2	(Dias et al., 2021)
<i>S. wightii</i>	Ethanol 70%	Soxhlet extraction	60°C; 6h; 1:15 (w/v)	45	(Panzella, 2020)
<i>S. muticum</i>	Methanol 50%	Ultrasonic-assisted	40°C; 30min; 20kHz; 1:25 (w/v)	30	(Schwartz et al., 2017)
<i>S. filipendula</i>	Aqueous extraction	Hot water extraction	80°C; 2h; 1:30 (w/v)	10	(Polo & Chow, 2022)
<i>S. latifolium</i>	Acetone 70%	Maceration	Room temp; 48h; 1:20 (w/v)	4.3	(Ahmed et al., 2024)

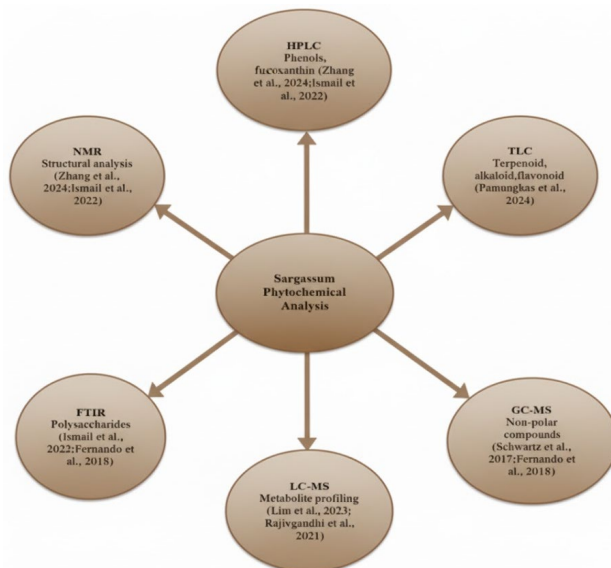


Figure 2. Analytical methods used in phytochemical analysis of *Sargassum* species

Sargassum, a genus of brown algae renowned for its bioactive compounds. High-performance liquid chromatography (HPLC) is routinely utilized to identify phenolic compounds and fucoxanthin, a carotenoid exhibiting antioxidant properties (Ismail et al., 2022; Zhang et al., 2024). Thin layer chromatography (TLC) facilitates the detection of terpenoids, alkaloids, and flavonoids (Pamungkas et al., 2024), while gas chromatography-mass spectrometry (GC-MS) effectively analyzes non-polar compounds, hydrocarbons, and fatty acids (Schwartz et al., 2017; Fernando et al., 2018). Additionally, liquid chromatography-mass spectrometry (LC-MS) serves a crucial role in metabolite profiling, enabling identification of diverse secondary metabolites (Rajivgandhi et al., 2021; Lim et al., 2023b). Beyond chromatographic approaches, spectroscopic techniques are vital for structural and functional analysis of *Sargassum* components. Nuclear magnetic resonance (NMR) spectroscopy is extensively utilized for detailed structural elucidation of organic compounds (Ismail et al., 2022; Zhang et al., 2024), while Fourier transform infrared spectroscopy (FTIR) proves particularly valuable for identifying polysaccharides, which are essential for algal cell wall structure and bioactive properties (Fernando et al., 2018; Ismail et al., 2022).

3. Analytical Methods for Phytochemical Analysis

3.1 Extraction techniques

Extraction methodology critically determined both the yield and bioactivity of *Sargassum*-derived phytochemicals (Table 3). Conventional solvent extraction demonstrated compound-specific selectivity, with polar solvents (methanol/ethanol) achieving 60-85% recovery of polyphenols and flavonoids, while non-polar solvents extracted 40-70% of

Table 3. Comparison of extraction methodologies for phytochemicals and polysaccharides from *Sargassum* species

Extraction Category	Method/Solvent	Target Compounds	Mechanism of Action	Yield	References
Conventional Solvent	Methanol/Ethanol (70-80%)	Polyphenols, flavonoids, alkaloids	Polar dissolution; cell membrane permeation	60-85% recovery	(Kumar et al., 2023; Lim et al., 2023b)
Conventional Solvent	Petroleum ether/Ethyl acetate	Terpenoids, carotenoids, fatty acids	Non-polar dissolution; lipid extraction	40-70% recovery	(Emu et al., 2023)
Conventional Solvent	Aqueous (water)	Polysaccharides, proteins	Hydrophilic dissolution maintains macromolecule integrity	5-12% yield	(Flores-Contreras et al., 2023)
Advanced Technology	Ultrasonic-assisted extraction (UAE)	Broad spectrum (polar & non-polar)	Cavitation-induced cell disruption; enhanced mass transfer	15-30% higher than conventional	(Mehta et al., 2022)
Polysaccharide-Specific	Alkaline (KOH 0.5-2 M or Na ₂ CO ₃)	Cellulose, sulfated polysaccharides	H-bond disruption; ester linkage cleavage	8-15% yield; 50-200 kDa MW	(Kalemtas et al., 2025)
Polysaccharide-Specific	Calcium chloride (CaCl ₂ 2-5%)	Fucoidan (sulfated fucose-rich)	Selective Ca ²⁺ -mediated precipitation	3-8% yield; 100-500 kDa MW	(Otero et al., 2023)
Polysaccharide-Specific	Acidic (HCl 0.1-1 M)	Oligosaccharides, low-MW polysaccharides	Glycosidic bond hydrolysis	5-12% yield; 5-50 kDa MW	(Wang et al., 2016)
Polysaccharide-Specific	Sequential (Alkaline→CaCl ₂ →Acid)	Comprehensive polysaccharide fractionation	Multi-step selective isolation	18-25% total yield; Variable MW	(Flores-Contreras et al., 2023)

lipophilic terpenoids and carotenoids (Emu et al., 2023; Kumar et al., 2023; Lim et al., 2023a). However, these methods required 24-48 h and substantial solvent volumes. In contrast, ultrasonic-assisted extraction (UAE) reduced processing time by 50-70% while increasing yields by 15-30%, particularly for thermolabile compounds, through cavitation-induced cell disruption and enhanced mass transfer (Mehta et al., 2022). For polysaccharide isolation, the extraction strategy fundamentally determines structural characteristics and molecular weight profiles. Alkaline extraction (KOH/Na₂CO₃) yielded 8-15% of high molecular weight (50-200 kDa) sulfated polysaccharides, while CaCl₂ extraction selectively targeted fucoidan with 3-8% yield but superior purity (Otero et al., 2023; Kalemintas et al., 2025). Acidic hydrolysis produced low molecular weight oligosaccharides (5-50 kDa) with 5-12% recovery, and sequential alkaline-CaCl₂-acid protocols achieved maximum total polysaccharide recovery of 18-25% with comprehensive fractionation enabling structure-activity relationship studies (Wang et al., 2016; Flores-Contreras et al., 2023). Despite these advances, standardization of extraction parameters across *Sargassum* species remains a critical gap in the research, as most studies focus on single-species optimization without comparative validation, limiting the reproducibility and scalability of bioactive compound production for industrial applications.

3.2 Analytical techniques

Table 4 summarizes a comprehensive overview of analytical methodologies employed in phytochemical characterization of *Sargassum* species, demonstrating the complementary nature of chromatographic, spectroscopic, and spectrometric techniques in elucidating the complex chemical composition of these marine macroalgae. Chromatographic techniques, together with thin-layer chromatography (TLC), gas chromatography-mass spectrometry (GC-MS), and liquid chromatography-mass spectrometry (LC-MS), serve as primary tools for compound separation and identification based on their physicochemical properties. TLC provides rapid preliminary screening for terpenoids, alkaloids, and flavonoids in *Turbinaria ornata*, a family within the Sargassaceae, offering a cost-effective method for qualitative analysis and monitoring extraction efficiency. GC-MS has been extensively utilized for analyzing volatile and semi-volatile non-polar compounds in *S. muticum*, enabling identification of fatty acids, hydrocarbons, and terpenoids through comparison with mass spectral libraries. The advancement to LC-MS and its high-resolution variant, quadrupole time-of-flight LC-MS (Q-TOF LC-MS), has revolutionized metabolite profiling by providing accurate mass measurements and structural information for a broader range of compounds, including thermolabile and polar metabolites that are incompatible with GC-MS analysis. These hyphenated techniques have facilitated the identification of numerous putative metabolites in various *Sargassum* species, significantly expanding our understanding of their metabolomic diversity.

Spectroscopic techniques complement chromatographic methods by providing detailed structural information essential for complete compound characterization and quality control of *Sargassum* extracts. Fourier transform infrared spectroscopy (FTIR) has emerged as an indispensable tool for polysaccharide characterization in multiple *Sargassum* species, such as *S. euryphyllum*, *S. aquifolium* and *S. horneri*, enabling identification of functional groups such as sulfate esters, carboxyl groups, and glycosidic linkages that define polysaccharide structure and biological activity. Nuclear magnetic resonance (NMR) spectroscopy, particularly proton (¹H-NMR) and carbon-13 (¹³C-NMR) techniques, provided unambiguous structural elucidation of isolated compounds from *S.*

Table 4. Analytical techniques used for phytochemical analysis of *Sargassum* species

Analytical Technique	Application	<i>Sargassum</i> Species	Reference
Gas Chromatography-Mass Spectrometry (GC-MS)	Analysis of non-polar compounds	<i>S. muticum</i>	(Schwartz et al., 2017)
Liquid Chromatography-Mass Spectrometry (LC-MS)	Metabolite profiling	<i>Sargassum</i> sp., <i>S. wightii</i>	(Rajivgandhi et al., 2021; Lim et al., 2023b)
Quadrupole Time-of-Flight LC-MS (Q-TOF LC-MS)	Identification of putative metabolites	<i>Sargassum</i> sp.	(Liu et al., 2020; Lim et al., 2023)
Fourier Transform Infrared Spectroscopy (FTIR)	Characterization of polysaccharides	<i>S. euryphyllum</i> , <i>S. aquifolium</i> , <i>S. horneri</i>	(Fernando et al., 2018; Ismail et al., 2022)
Nuclear Magnetic Resonance (NMR)	Structural analysis of compounds	<i>S. fusiforme</i>	(Zhang et al., 2024)
High-Performance Liquid Chromatography (HPLC)	Analysis of fucoxanthin, phenols	<i>S. fusiforme</i>	(Zhang et al., 2024)
Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)	Elemental analysis	<i>S. horneri</i>	(Fernando et al., 2018)

fusiforme, revealing stereochemistry, connectivity, and conformational information critical for structure-activity relationship studies. High-performance liquid chromatography (HPLC), often coupled with photodiode array (PDA) or fluorescence detection, enabled quantitative analysis of specific bioactive compounds such as fucoxanthin and phenolic compounds in *S. fusiforme*, offering high sensitivity and reproducibility essential for standardization and quality assurance.

4. Biological Activities of *Sargassum* Phytochemicals

4.1 Antimicrobial activity

Analytical methodologies employed in the phytochemical characterization of *Sargassum* species demonstrate the complementary nature of chromatographic, spectroscopic, and spectrometric techniques in elucidating the complex chemical composition of these marine macroalgae (Table 5). The data highlights the efficacy of different extract types, as well as n-hexane, petroleum ether, and nano-encapsulated extracts, in inhibiting bacterial and fungal growth. For instance, n-hexane extract of *S. polycystum* exhibited potent antibacterial activity against *Bacillus cereus*, with a minimum inhibitory concentration (MIC) of 0.065 mg/mL. Similarly, *S. filipendula* and *S. hystrix* exhibited broad-spectrum inhibition of *Staphylococcus aureus*, *Bacillus subtilis*, and *Trichophyton mentagrophytes* at 0.78-6.25 mg/mL, indicating that different *Sargassum* species contain potent bioactive compounds against bacterial and fungal pathogens. Additionally, *S. cristaefolium* and *S. aquifolium* exhibited substantial antibacterial activity against *Escherichia coli* and

Edwardsiella tarda, as evidenced by significant inhibition zones and antibacterial effects. A petroleum ether extract of *S. aquifolium* was particularly recognized for its robust antibacterial properties, while *Sargassum* extract encapsulated in chitosan-tripolyphosphate (TPP) nanoparticles demonstrated enhanced antibacterial activity against *Escherichia coli* and *Salmonella* sp., suggesting that advanced extraction or delivery systems may augment antimicrobial efficacy.

Table 5. Antimicrobial activity of *Sargassum* species

Sargassum Species	Extract Type	Target Organisms	Key Findings	Reference
<i>S. polycystum</i>	n-hexane extract	<i>Bacillus cereus</i>	MIC = 0.065 mg/mL	(MG & MG, 2021)
<i>S. filipendula</i> , <i>S. hystrix</i>	Not specified	<i>Staphylococcus aureus</i> , <i>Bacillus subtilis</i> , <i>Trichophyton mentagrophytes</i>	Inhibition at 0.78-6.25 mg/mL	(Morales et al., 2006) (Telles et al., 2018)
<i>S. cristaefolium</i>	Not specified	<i>Escherichia coli</i> , <i>Edwardsiella tarda</i>	Inhibition zones of 14.03±2.97 mm and 10.60±0.72 mm, respectively	(Dewinta et al., 2023)
<i>S. aquifolium</i>	Petroleum ether extract	<i>Escherichia coli</i>	Significant antibacterial activity	(Moni et al., 2021)
<i>Sargassum</i> sp.	Extract encapsulated in chitosan-TPP nanoparticles	<i>Escherichia coli</i> , <i>Salmonella</i> sp.	Enhanced antibacterial activity compared to free extract	(Andri et al., 2023)
<i>S. polycystum</i>	n-hexane extract	<i>Bacillus cereus</i>	MIC = 0.065 mg/mL	(Bolaños et al., 2017) (Chong et al., 2011)
<i>S. cristaefolium</i>	methanol	<i>Staphylococcus</i>	MIC = 0.075 mg/mL	(Shanmugam et al., 2014)

Table 5 summarizes the antimicrobial efficacy of selected *Sargassum* extracts, demonstrating a clear relationship between extract polarity and antibacterial potency. An

n-hexane extract of *Sargassum polycystum* showed exceptional activity against *Bacillus cereus*, with a remarkably low MIC of 0.065 mg/mL, indicating the presence of highly bioactive lipophilic metabolites. These non-polar compounds, likely terpenoids or long-chain fatty acids, exhibit strong antibacterial effects consistent with the selective extraction capability of n-hexane. A methanol extract of *S. cristaefolium* also showed antibacterial activity against *Escherichia coli* and *Edwardsiella tarda*, with inhibition zones of 14.03 ± 2.97 mm and 10.60 ± 0.72 mm, respectively (Dewinta et al., 2023), reflecting the contribution of polar and semi-polar metabolites such as phenolics and flavonoids. Similar MIC values for non-polar and polar extracts highlighted the chemical diversity of *Sargassum*, indicating that bioactive compounds across a broad polarity range can exert potent antimicrobial effects. The consistently low MIC values highlight the high potency of *Sargassum*-derived extracts, supporting their potential as natural antimicrobial agents effective at minimal concentrations. These findings underscore the potential of *Sargassum* as a source of alternative antimicrobials, especially amid increasing resistance in Gram-positive pathogens such as *Staphylococcus* and *Bacillus* species. The variation in antibacterial activity across solvent types also highlights the importance of optimizing extraction strategies to maximize recovery of target antimicrobial constituents.

4.2 Antioxidant activity

The comprehensive antioxidant data across multiple assays demonstrate the strong free radical scavenging capacity of *Sargassum* phytochemical fractions, highlighting their potential as natural antioxidants for pharmaceutical and nutraceutical applications (Table 6). The data reveal substantial interspecies variation in antioxidant capacity, with *S. wightii* exhibiting the highest DPPH radical scavenging activity at $75.49 \pm 0.12\%$, followed closely by *S. latifolium* methanol extract demonstrating 74.8% ferric reducing antioxidant power (FRAP). These findings underscore the significant antioxidant potential of *Sargassum* species, with activities comparable to or exceeding those of many terrestrial plant sources and synthetic antioxidants. The variation in antioxidant activity among species likely reflects differences in phytochemical composition, particularly the concentration and structural diversity of phenolic compounds, flavonoids, and other reducing agents. Notably, *S. aquifolium* polysaccharides exhibited $65.25 \pm 2.89\%$ DPPH scavenging activity, while *S. euryphyllum* polysaccharides showed $59.15 \pm 2.75\%$ activity, indicating that sulfated polysaccharides themselves possess inherent antioxidant properties independent of associated phenolic compounds. This observation is particularly significant as it suggests that multiple phytochemical classes contribute synergistically to the overall antioxidant capacity of *Sargassum* extracts.

The employment of different antioxidant assays provides complementary insights into the mechanisms underlying the antioxidant activities of *Sargassum* extracts. The DPPH assay, used for most samples in Table 5, measures antioxidants' ability to donate hydrogen atoms or electrons to neutralize stable radicals, providing a reliable indicator of radical scavenging capacity. The FRAP (ferric reducing antioxidant power) assay employed for *S. latifolium* measures the reduction of ferric ions (Fe^{3+}) to ferrous ions (Fe^{2+}), reflecting the electron-donating capacity and reducing power of antioxidant compounds (Gülçin, 2015). The hydrogen peroxide (H_2O_2) scavenging assay used for *S. polycystum* fucoidan fraction F2, which demonstrated $71.76 \pm 2.14\%$ activity, is particularly relevant for assessing protective effects against oxidative stress, as H_2O_2 serves as a precursor to highly reactive hydroxyl radicals implicated in cellular damage and various pathological conditions (Park et al., 2018). The superior performance of fucoidan fraction F2 in H_2O_2

scavenging compared to DPPH scavenging ($55.94 \pm 0.69\%$) suggests that sulfated polysaccharides may exhibit mechanism-specific antioxidant activities, with enhanced efficacy against certain reactive oxygen species. This variation in activity underscores the need for multiple antioxidant assays to comprehensively assess natural extracts' protective capacity against diverse forms of oxidative stress.

Table 6. Antioxidant activity of *Sargassum* species

Sargassum Species	Extract/Compound	Antioxidant Assay	Key Findings	Reference
<i>S. euryphyllum</i>	Polysaccharides	DPPH assay	$59.15 \pm 2.75\%$ scavenging activity	(Ismail et al., 2022)
<i>S. aquifolium</i>	Polysaccharides	DPPH assay	$65.25 \pm 2.89\%$ scavenging activity	(Ismail et al., 2022)
<i>S. latifolium</i>	Methanol extract	FRAP assay	74.8% scavenging power	(Ahmed et al., 2024)
<i>S. polycystum</i> (fraction F2)	Fucoidan	DPPH assay	$55.94 \pm 0.69\%$ scavenging activity	(Palanisamy et al., 2018)
<i>S. polycystum</i> (fraction F2)	Fucoidan	H ₂ O ₂ scavenging	$71.76 \pm 2.14\%$ scavenging activity	(Palanisamy et al., 2018)
<i>S. polycystum</i>	Fucoidan fraction F2	H ₂ O ₂ scavenging assay	$71.76 \pm 2.14\%$ scavenging activity	(Park et al., 2018)

4.3 Anti-inflammatory activity

Compelling evidence for the anti-inflammatory properties of various *Sargassum* species through multiple mechanistic pathways demonstrates their potential as natural anti-inflammatory agents for managing chronic and acute inflammatory responses (Table 7). The data reveals that different *Sargassum* species and their isolated compounds target distinct inflammatory mediators and signaling cascades, suggesting broad-spectrum anti-inflammatory activity. *S. micracanthum* ethanol extract demonstrated significant inhibition of lipopolysaccharide (LPS)-induced inflammatory responses, effectively suppressing nitric oxide (NO) production and reducing the expression of key pro-inflammatory cytokines, interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF- α), and interleukin-1 beta (IL-1 β). The ability of *S. micracanthum* extract to simultaneously modulate multiple inflammatory mediators suggests the presence of diverse anti-inflammatory compounds or synergistic interactions among phytochemical constituents, potentially offering advantages over single-target synthetic anti-inflammatory drugs.

Table 7. Anti-inflammatory activity of *Sargassum* species

Sargassum Species	Compound	Model/Assay	Key Findings	Reference
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<i>S. micracanthum</i>	Ethanol extract	LPS-induced inflammatory response	Inhibition of NO production and inflammatory cytokines (IL-6, TNF- α , IL-1 β)	(Jeong et al., 2013)
<i>S. horneri</i>	Alginic acid	HaCaT keratinocytes exposed to fine dust	Reduced COX-2, PGE2, IL-6, and TNF- α levels; inhibition of NF- κ B and MAPK pathways	(Fernando et al., 2018)
<i>S. latifolium</i>	Not specified	Cox1 inhibition assay	76.08% Cox1 inhibition	(Ahmed et al., 2024)

Studies on *S. horneri* alginic acid revealed molecular-level anti-inflammatory effects through inhibition of key intracellular signaling pathways. When HaCaT keratinocytes were exposed to fine particulate matter, a clinically relevant model of environmental pollutant-induced skin inflammation, alginic acid treatment significantly reduced the expression of cyclooxygenase-2 (COX-2) and prostaglandin E2 (PGE2), which are a key enzyme and mediator in the arachidonic acid cascade responsible for pain, fever, and inflammation (Bocheva et al., 2023). Moreover, the observed reduction in IL-6 and TNF- α levels, coupled with inhibition of nuclear factor kappa B (NF- κ B) and mitogen-activated protein kinase (MAPK) pathways, demonstrate that *Sargassum* polysaccharides can interfere with upstream regulatory mechanisms controlling inflammatory gene expression (Jayasinghe et al., 2022). NF- κ B is a master transcription factor regulating numerous genes in inflammation, immunity, and cell survival, whereas MAPK pathways mediate cellular responses to inflammatory and environmental stress (Liu et al., 2017). The dual inhibition of these pathways suggests that alginic acid from *S. horneri* possesses potent anti-inflammatory efficacy with potential applications in dermatological conditions, respiratory inflammation caused by air pollution, and other inflammatory disorders triggered by environmental toxins. *Sargassum* extracts exhibit a multi-targeted approach, simultaneously modulating cytokine production, enzyme activity, and intracellular signaling pathways. This strategy may offer superior therapeutic effects compared to single-target anti-inflammatory drugs while reducing the risk of adverse effects from complete pathway inhibition.

4.4 Antidiabetic and metabolic effects

Table 8 presents comprehensive evidence for the antidiabetic and metabolic regulatory effects of various *Sargassum* species, demonstrating their potential as natural therapeutic agents for managing type 2 diabetes mellitus and associated metabolic disorders (Hameed et al., 2015). The data reveal multiple mechanisms by which *Sargassum* compounds confer metabolic benefits, including enzyme inhibition, improved glucose homeostasis, lipid profile modulation, and reduction of oxidative stress. The enzyme inhibition studies conducted

Table 8. Antidiabetic and metabolic effects of *Sargassum* species

<i>Sargassum</i> Species	Compound	Model/Assay	Key Findings	Reference
<i>S. wightii</i>	Petroleum ether and ethyl acetate extracts	α -amylase and α -glucosidase inhibition assays	α -amylase (IC ₅₀ 378.3 μ g/ml) and α -glucosidase (IC ₅₀ 314.8 μ g/ml) inhibition	(Unnikrishnan et al., 2015)
<i>S. yezoense</i>	Not specified	db/db mice	Improved glucose and lipid parameters without side effects	(Kim et al., 2012)
<i>S. angustifolium</i>	Ethanol fraction	Dexamethasone-induced dyslipidemic rats	Decreased serum blood sugar, triglycerides, total cholesterol, LDL-C, and MDA levels	(Yegdaneh et al., 2022)
<i>S. latifolium</i>	Combined with laser treatment	Hypercholesterolemic rats	Improved HDL-C and reduced total lipids, triglycerides, total cholesterol, LDL-C, and VLDL-C	(Ahmed et al., 2024)

with *S. wightii* petroleum ether and ethyl acetate extracts provide crucial mechanistic insights into the antidiabetic potential of *Sargassum* phytochemicals. The observed inhibition of α -amylase (IC₅₀ = 378.3 μ g/mL) and α -glucosidase (IC₅₀ = 314.8 μ g/mL) indicates moderate to potent activity against these enzymes, which hydrolyze polysaccharides and disaccharides into absorbable monosaccharides in the gastrointestinal tract. The slightly stronger inhibition of α -glucosidase compared to α -amylase is advantageous, as selective α -glucosidase inhibition delays glucose absorption without fully blocking carbohydrate digestion. The mechanism underlying enzyme inhibition likely involves interactions between phenolic compounds, flavonoids, and other bioactive constituents present in *S. wightii* extracts and the active sites or allosteric regulatory regions of digestive enzymes. Phenolic compounds can form hydrogen bonds and hydrophobic interactions with amino acid residues in enzyme binding pockets, competing

with substrate binding and reducing catalytic efficiency (Shahidi & Dissanayaka, 2023). The use of petroleum ether and ethyl acetate extracts, which selectively extract semi-polar and moderately polar compounds, suggests that terpenoids, phenolic acids, and flavonoid aglycones contribute significantly to enzyme inhibitory activity.

In vivo studies validate the antidiabetic and lipid-modulating efficacy of *Sargassum* species under physiologically relevant conditions. *S. yezoense* administration in db/db mice, a genetic model of type 2 diabetes with leptin receptor deficiency, improved glucose homeostasis and reduced triglycerides, total cholesterol, and LDL-C without adverse effects, addressing the dyslipidemia characteristic of type 2 diabetes. Similarly, an ethanol fraction of *S. angustifolium* protected against dexamethasone-induced metabolic dysfunction in rats by decreasing serum glucose, triglycerides, total cholesterol, LDL-C, and malondialdehyde (MDA) levels, suggesting therapeutic potential for patients receiving chronic glucocorticoid therapy who face elevated diabetes and cardiovascular risks (Madamsetty et al., 2022). The antioxidant compounds in *S. angustifolium*, including polyphenols and fucoxanthin, likely scavenge reactive oxygen species and enhance endogenous antioxidant defenses, thereby interrupting pathogenic cascades linking hyperglycemia and dyslipidemia to tissue damage. Furthermore, *S. latifolium* combined with low-level laser treatment in hypercholesterolemic rats demonstrated synergistic effects, improving HDL-C while reducing total lipids, triglycerides, total cholesterol, LDL-C, and VLDL-C, indicating comprehensive lipid profile modulation that addresses multiple dyslipidemia aspects (Velissaridou et al., 2024). These findings collectively demonstrate that *Sargassum* extracts exert multifaceted metabolic benefits through antioxidant mechanisms and lipid regulation across diverse diabetic and dyslipidemic models.

4.5 Anticancer and cytotoxic activity

Compelling evidence for the anticancer potential of *Sargassum* species against multiple human cancer cell lines demonstrates their selective cytotoxicity and therapeutic promise for oncological applications (Table 9). The data reveal significant variation in potency across different species and cell line types, with *S. polycystum* fucoidan fraction F2 exhibiting the most potent cytotoxic activity with half-maximal inhibitory concentration (IC_{50}) values of 20 $\mu\text{g/mL}$ against MCF-7 breast cancer cells and 50 $\mu\text{g/mL}$ against HCT-15 colorectal cancer cells. These relatively low IC_{50} values indicate substantial cytotoxic potency and suggest that sulfated polysaccharides, particularly fucoidans, represent promising lead compounds for anticancer drug development. The differential sensitivity between cancer cell lines, with MCF-7 cells showing 2.5-fold greater susceptibility than HCT-15 cells, suggests cell type-specific mechanisms of action. This may be related to differences in cell surface receptor expression, signaling pathways, or metabolic characteristics between breast and colorectal cancer cells. This selectivity is advantageous from a therapeutic perspective, as it may enable targeted treatment strategies tailored to specific cancer types. The fucoidan fraction from *S. polycystum* appears to be a refined preparation with enhanced bioactivity, highlighting the importance of fractionation and purification processes in maximizing the therapeutic potential of marine-derived polysaccharides.

Table 9. Anticancer and cytotoxic activity of *sargassum* species

<i>Sargassum</i> Species	Compound	Cancer Cell Lines	Key Findings	Reference
<i>S. polycystum</i> (fraction F2)	Fucoidan	MCF-7, HCT-15	IC ₅₀ values of 20 and 50 µg/mL, respectively	(Palanisamy et al., 2018)
<i>S. oligocystum</i>	Water extract	Daudi, K562	Effective at 500 µg/mL and 400 µg/mL, respectively	(Zandi et al., 2010)

The anticancer activity of *S. oligocystum* water extract against hematological malignancies highlights the versatility of *Sargassum*-derived compounds across diverse cancer types. The extract exhibited effectiveness against Daudi Burkitt's lymphoma cells at 500 µg/mL and K562 chronic myelogenous leukemia cells at 400 µg/mL, indicating moderate cytotoxic activity that, while less potent than the purified fucoidan fraction, still demonstrates therapeutic relevance, particularly considering the simplicity of water extraction, which offers practical advantages for large-scale production and cost-effectiveness. The activity against hematological cancer cell lines is particularly significant as these malignancies often exhibit resistance to conventional chemotherapeutic agents and require novel therapeutic approaches. The comparison of *S. wightii* extract with doxorubicin, a widely used anthracycline chemotherapy agent considered a reference standard in cancer treatment, provides crucial context for evaluating clinical relevance. The observation that *S. wightii* extract demonstrated strong cytotoxic activity comparable to doxorubicin against Caco-2 cell lines, colorectal adenocarcinoma and HepG2 hepatocellular carcinoma is remarkable, suggesting that this species contains potent anticancer compounds with efficacy approaching that of established chemotherapeutic drugs. This finding is particularly encouraging given the severe cardiotoxicity and other adverse effects associated with doxorubicin, which limit its clinical utility and patient quality of life (Vitale et al., 2024).

The mechanisms underlying the anticancer activities of *Sargassum* extracts likely involve multiple pathways, induction of apoptosis through intrinsic and extrinsic pathways, cell cycle arrest at specific checkpoints, inhibition of angiogenesis essential for tumor growth and metastasis, modulation of immune responses to enhance tumor recognition and destruction, and direct cytotoxic effects through membrane disruption or metabolic interference. Fucoidans, in particular, have been extensively studied for their immunomodulatory properties and ability to activate natural killer cells and macrophages, suggesting that their anticancer effects may involve both direct cytotoxicity and indirect enhancement of anti-tumor immunity. The structural features of fucoidans, together with molecular weight, degree of sulfation, and glycosidic linkage patterns, significantly influence their biological activities, and optimization of these parameters through controlled extraction and modification processes may yield derivatives with enhanced anticancer potency and selectivity (Zueva et al., 2023).

4.6 Antiviral activity

The antiviral activities of *Sargassum* species demonstrated exceptional therapeutic potential, particularly the polysaccharide fraction SFP4 from *S. fusiforme*, which exhibited a remarkable therapeutic index exceeding 139 against respiratory syncytial virus (RSV), indicating a wide safety margin where antiviral efficacy is achieved at concentrations far

below those causing cellular toxicity (Table 10). The prophylactic effectiveness of SFP4 is especially significant for clinical applications, as prevention of viral infection proves more effective than treating established disease, particularly for viruses like RSV, lacking specific therapies. Systematic studies on *S. polycystum* polysaccharide fractions have shown that different extraction approaches targeting specific polysaccharide groups produce cellulose-enriched (67.02 µg/mL), alginate-enriched (33.25 µg/mL), and fucoidan-enriched (31.62 µg/mL) fractions with antiviral activity (Ningsih et al., 2020). These results indicate that antiviral effects are likely driven by multiple structurally diverse polysaccharides rather than a single compound type. The exceptional performance of *S. filipendula* aqueous extract, achieving approximately 100% viral inhibition at merely 50 µg/mL, combined with simple and safe extraction methods, positions it as an attractive candidate for cost-effective, environmentally friendly antiviral product development.

Table 10. Antiviral activity of *sargassum* species

Sargassum Species	Natural Product Groups	Virus/Assay	Key Findings	Reference
<i>S. fusiforme</i> (SFP4)	Polysaccharide	Respiratory Syncytial Virus (RSV)	Therapeutic index (TI) > 139; effective as prophylactic treatment	(Zhang et al., 2024)
<i>S. polycystum</i>	KOH 4M (cellulose) solution	Not specified	67.02 µg/mL of antiviral compounds	(Ningsih et al., 2020)
<i>S. polycystum</i>	Na ₂ CO ₃ 3% (alginates)	Not specified	33.25 µg/mL of antiviral compounds	(Ningsih et al., 2020)
<i>S. polycystum</i>	CaCl ₂ 2% (fucoidan)	Not specified	31.62 µg/mL of antiviral compounds	(Ningsih et al., 2020)
<i>S. filipendula</i>	Aqueous extracts	Not specified	~100% efficiency even at 50 µg/ml	(Polo & Chow, 2022)

These antiviral activities have profound implications for addressing global health challenges posed by viral infections, particularly regarding emerging diseases, antiviral drug resistance, and limited therapeutic options. Marine-derived polysaccharides from *Sargassum* species offer several advantages over conventional antiviral drugs (Kumar et al., 2025), potentially lower toxicity due to structural similarity to endogenous glycosaminoglycans, reduced likelihood of inducing viral resistance through multi-targeted mechanisms differing from nucleoside analogs and protease inhibitors, immunomodulatory

properties enhancing host antiviral responses beyond direct antiviral effects, and potential for topical or mucosal administration preventing respiratory and mucosal viral infections. The mechanism of action, particularly for fucoidans from *S. henslowianum* against enveloped viruses (influenza, herpes simplex, HIV, coronaviruses), involves interference with viral attachment and entry by mimicking cell surface glycosaminoglycans, electrostatically blocking viral binding sites, and preventing conformational changes required for membrane fusion (Lomartire & Gonçalves, 2022). The demonstrated prophylactic efficacy is particularly relevant for pandemic preparedness and control of seasonal respiratory infections (He et al., 2023), potentially offering protective strategies for healthcare workers, high-risk populations, and community settings where viral transmission risk is elevated.

4.7 Other biological activities

The diverse biological activities of *Sargassum* species that extend beyond traditional pharmaceutical applications demonstrate the multifaceted utility of these marine macroalgae in veterinary medicine, sustainable agriculture, and environmental remediation (Table 11). The antiparasitic activity of *S. polycystum* methanol extract represents a significant finding with implications for both human and animal health, particularly in regions where parasitic infections pose substantial health burdens. The extract demonstrated remarkable efficacy, achieving 100% mortality of leeches in less than one minute (0.96 ± 0.44 min) at a concentration of 100 mg/mL, indicating potent and rapid-acting antiparasitic properties. This exceptionally short time to complete mortality suggests acute toxicity mechanisms, likely involving disruption of parasitic neuromuscular function, osmotic balance, or integumental integrity through bioactive compounds such as phenolics, terpenes, or alkaloids present in the methanol extract.

The application of *Sargassum* extracts as agricultural biostimulants represents an innovative and sustainable approach to enhancing crop productivity while reducing dependence on synthetic fertilizers and chemical growth regulators. Biostimulants are substances or microorganisms that, when applied to plants or the rhizosphere, stimulate natural processes to enhance nutrient uptake efficiency, stress tolerance, and crop quality characteristics (Du Jardin, 2015). *Sargassum* extracts contain diverse bioactive compounds, plant growth hormones (auxins, cytokinins, gibberellins), polysaccharides (alginates, fucoidans), amino acids, vitamins, minerals, and phenolic compounds that collectively contribute to biostimulant effects (Ali et al., 2021). The promotion of plant growth reported for *Sargassum* extracts manifests through multiple mechanisms, such as the enhancement of root development and architecture leading to improved water and nutrient acquisition, stimulation of photosynthetic efficiency and chlorophyll biosynthesis, modulation of plant hormone signaling pathways controlling cell division and elongation, and activation of metabolic processes supporting biomass accumulation. The polysaccharides and phenolic compounds in *Sargassum* extracts induce plant defense mechanisms, enhance antioxidant enzyme activities, stabilize cell membranes under stress conditions, and promote osmolyte accumulation for osmotic adjustment (Sofy et al., 2017).

Table 11. Other biological activities of *sargassum* species

<i>Sargassum</i> Species	Extract/Compound	Activity	Key Findings	Reference
<i>S. polycystum</i>	Methanol extract	Antiparasitic (leech)	100% leech mortality in 0.96±0.44 min at 100 mg/mL	(Haron et al., 2022)
<i>Sargassum</i> sp.	Various extracts	Agricultural biostimulant	Promotion of plant growth, nutrient uptake, and stress tolerance	(Senthilkumar et al., 2024)
<i>Sargassum waste</i>	Microbiome	Bioremediation	Potential for xenobiotic bioremediation	(Mohapatra, 2023)

The bioremediation potential of *Sargassum* waste microbiome represents an emerging and highly innovative application that addresses both environmental pollution and waste management challenges. The microbiome associated with *Sargassum* biomass, comprising diverse bacterial, archaeal, and fungal communities, has demonstrated capacity for xenobiotic bioremediation, referring to the microbial degradation or transformation of synthetic organic compounds, pesticides, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, pharmaceuticals, and industrial chemicals that persist in environmental matrices (Mohapatra, 2023). *Sargassum* waste can serve as an abundant, low-cost bioremediation resource by providing microbial inocula, organic substrates, and opportunities for bioaugmentation and integrated biorefinery applications. The functional characterization of *Sargassum* microbiomes has revealed diverse metabolic capabilities including hydrocarbon degradation, aromatic compound catabolism, heavy metal resistance and transformation, and production of biosurfactants facilitating pollutant bioavailability and degradation.

Figure 3 illustrates the biological activities of various *Sargassum* species based on compiled data from studies conducted between 2006 and 2024. The biological activities presented include antimicrobial, antioxidant, anti-inflammatory, antidiabetic, anticancer, antiviral, antiparasitic, and additional properties. Darker colors indicate stronger activity levels, while lighter colors represent lower or minimal activity. Blank cells indicate the absence of reported data for specific activities in particular species. The data reveal that several *Sargassum* species, *S. polycystum*, *S. wightii*, and *S. aquifolium*, demonstrated robust activity across multiple categories, particularly as antimicrobial, antioxidant, and antidiabetic agents. For example, *S. polycystum* displayed strong antimicrobial, antioxidant, and antiparasitic activities, as well as notable antiviral and anticancer effects. Meanwhile, *S. latifolium* and *S. fusiforme* display prominent antioxidant and anti-inflammatory activities. Other species, such as *S. horneri* and *S. yezoense*, showed limited activity in certain categories but retain biological potential meriting further exploration.

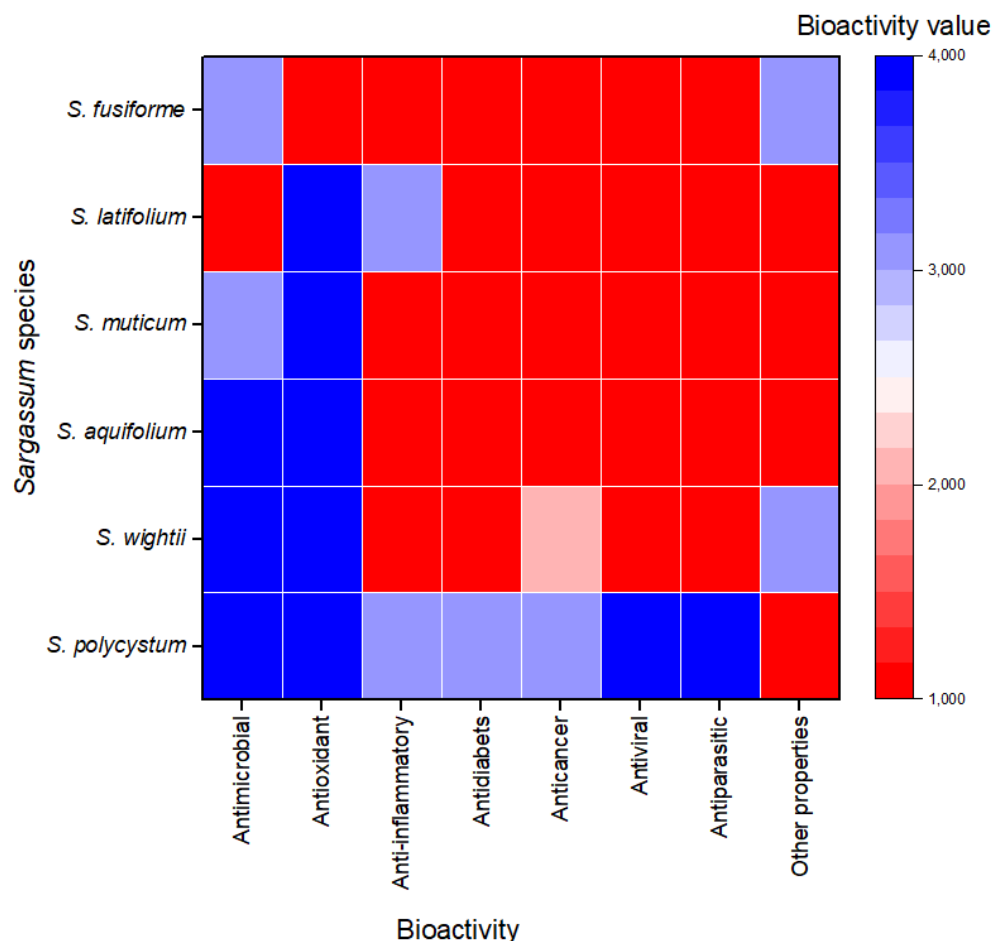


Figure 3. Biological activities of different *Sargassum* species

5. Future Perspectives and Applications

5.1 Pharmaceutical applications

The pharmaceutical potential of *Sargassum* species is strongly shaped by both geographic origin and extraction strategy, as these factors govern the type and abundance of bioactive phytochemicals recovered. For example, Indian Ocean *S. wightii* yielded high levels of antimicrobial phlorotannins when extracted with methanol, showing effective activity against antibiotic-resistant bacteria, with MIC values of 125-250 µg/mL against *Staphylococcus aureus* and *Escherichia coli* (Shannon & Abu-Ghannam, 2016). This highlights the suitability of polar solvents for isolating antibacterial phenolic compounds from region-specific species. Distinct pharmaceutical profiles are also evident among Pacific and Southeast Asian species. Sequential hot water–ethanol extraction of Pacific *S. fusiforme* produces fucoidans with high sulfate content, which displayed selective cytotoxicity toward cancer cells by inducing apoptosis, as reflected by an IC₅₀ of 85 µg/mL against HeLa cells (Pádua et al., 2015). In Southeast Asia, ultrasonic-assisted extraction

of *S. polycystum* enhanced fucoxanthin recovery, resulting in strong anti-inflammatory activity through NF- κ B pathway inhibition and a high antioxidant capacity, achieving 78% DPPH radical scavenging (Saraswati et al., 2019). Atlantic *Sargassum* species further illustrate how extraction-driven selectivity can guide pharmaceutical applications. Aqueous extracts of *S. muticum* preferentially yielded low-molecular-weight fucoidans with potent α -glucosidase inhibitory activity, supporting their potential in diabetes management. Meanwhile, enzyme-assisted extraction of *S. filipendula* maximized phlorotannin recovery, reaching 8-12% of dry weight, and produces compounds with notable neuroprotective properties, including acetylcholinesterase inhibition relevant to Alzheimer's disease therapy (Naeem et al., 2022; Monroy-García et al., 2025).

5.2 Cosmeceutical applications

The cosmeceutical performance of *Sargassum* extracts is strongly influenced by species origin and extraction strategy, reflecting substantial variation in phytochemical composition. Pacific *S. horneri*, for instance, yielded high levels of fucoxanthin and mycosporine-like amino acids when extracted with 70% ethanol. These compounds provide broad-spectrum UV protection and significantly suppress MMP-1 expression by 45%, highlighting their potential to mitigate photoaging at the molecular level (Pangestuti et al., 2021). Other species exhibit distinct cosmetic benefits when processed using targeted extraction methods. Acetone extracts of Indian Ocean *S. ilicifolium* showed potent tyrosinase inhibition, achieving an IC_{50} of 38 μ g/mL and reducing melanin production by 52%. Importantly, this effect is achieved without the safety concerns associated with conventional depigmenting agents such as hydroquinone, supporting its use in hyperpigmentation management (Puteri & Sumadi, 2024). In the Mediterranean region, supercritical CO_2 extraction of *S. vulgare* yielded fractions selectively enriched in fucosterol and fucoxanthin derivatives, which stimulated collagen synthesis by 38% and reduced wrinkle depth by 28% in clinical evaluations, demonstrating tangible anti-aging benefits (Budzianowska et al., 2025). Hydration and anti-inflammatory effects are also species-dependent. Aqueous-ethanol extracts of Southeast Asian *S. cristaefolium*, rich in sulfated polysaccharides, improved skin hydration by 42% while simultaneously suppressing COX-2 activity, indicating dual moisturizing and anti-inflammatory functionality (Khajure & Rasal, 2024). Meanwhile, enzymatic hydrolysis of Chinese *S. thunbergii* generated low-molecular-weight bioactive peptides with strong and photostable ROS-scavenging capacity, maintaining antioxidant efficacy even under prolonged UV exposure (Alves et al., 2020; Mucha et al., 2025). Together, these findings underscore that cosmeceutical efficacy cannot be generalized across *Sargassum* species. Instead, region-specific phytochemical profiles demand tailored extraction approaches to maximize the recovery of functionally relevant compounds for targeted skincare applications, ranging from photoprotection and pigmentation control to hydration and anti-aging.

5.3 Agricultural applications

The agricultural biostimulant performance of *Sargassum* extracts clearly depends on both species origin and extraction method, reflecting underlying differences in phytochemical composition. For example, alkaline extracts of Atlantic *S. vulgare*, which are rich in alginates and phytohormones, increased tomato shoot biomass by 32% and yield by 28% by promoting more developed root systems (El Boukhari et al., 2020). In contrast, hot water extracts of Indian Ocean *S. wightii*, characterized by high mineral content, reduced nitrogen

fertilizer requirements in wheat by up to 40% while maintaining yield, largely through improved nutrient use efficiency (Senthilkumar et al., 2024). Beyond growth promotion, some *Sargassum* species act as effective stress-response modulators. Fermented Atlantic *S. muticum* generated oligosaccharide elicitors that activate systemic acquired resistance in grapevines, reducing *Botrytis* infection by 65% (Qamer et al., 2021). Pacific species show particular advantages under abiotic stress, with acid-hydrolyzed *S. fusiforme* extracts enabling rice to retain 78% of yield under high salinity by enhancing proline accumulation, while ultrasonic aqueous extracts of *S. horneri* improved lettuce water-use efficiency by 42% under drought through the action of betaines and polyamines (Singh et al., 2015; Morales et al., 2020; Liang et al., 2022). Regional applications further highlight the importance of species selection. Cold-pressed extracts of Australian *S. plagiophyllum*, containing brassinosteroids, accelerated flowering and increased canola seed yield by 22% in phosphorus-limited soils (Dhaliwal et al., 2022). Similarly, composted Caribbean *S. natans* extracts improved maize yield by 18% under heat stress by enhancing soil organic matter and supplying trace elements (Heidarzadeh, 2025; Khoulati et al., 2025). Collectively, these studies demonstrate that aligning region-specific *Sargassum* species and extraction strategies with crop type and environmental stressors is critical for maximizing agricultural benefits. Phytochemical variation among species underpins distinct mechanisms of growth promotion, nutrient efficiency, and stress tolerance, reinforcing the need for targeted rather than generalized biostimulant applications.

5.4 Challenges and future research directions

Figure 4 illustrates the translational pathway from *Sargassum* biodiversity to practical application, highlighting how several key species (*S. polycystum*, *S. wightii*, *S. muticum*, *S. latifolium*, *S. fusiforme*, *S. euryphyllum*, and *S. aquifolium*) produce compounds in the eight major phytochemical classes (phenolics, flavonoids, alkaloids, terpenoids, pigments, polysaccharides, sterols, and tannins) that confer multiple biological properties, including antimicrobial, antioxidant, anti-inflammatory, antidiabetic, anticancer, antiviral, and antiparasitic activities. These diverse bioactivities provide the foundation for pharmaceutical, cosmeceutical, and agricultural applications reviewed in this study.

Despite promising findings throughout this review, several critical challenges must be addressed to translate *Sargassum* phytochemicals into commercial applications. Standardization of extraction and analytical methods represents a fundamental prerequisite, as current methodological heterogeneity complicates inter-study comparisons essential for evidence synthesis and clinical translation. Elucidating structure-activity relationships for key bioactive compounds constitutes a critical priority that would enable rational design of optimized derivatives with enhanced efficacy and pharmacological properties. Systematic approaches examining relationships between molecular structures, polysaccharide sulfation patterns, molecular weight, phenolic hydroxylation patterns, and glycosylation, and their biological activities would guide optimization of extraction procedures and compound selection for specific applications. Developing efficient, sustainable extraction processes for industrial-scale production remains a technical challenge and economic imperative. This requires green extraction technologies, process optimization via response surface methodology and AI, and biorefinery approaches for full valorization of *Sargassum* biomass.

Clinical trials validating the efficacy and safety of *Sargassum*-derived compounds represent the ultimate requirement for pharmaceutical applications, yet remain notably scarce despite extensive preclinical evidence. Systematic progression through Phase I

safety studies, Phase II dose-ranging efficacy studies, and Phase III large-scale randomized controlled trials requires substantial financial investment, specialized infrastructure, and collaborative networks involving academic institutions, clinical research organizations, and pharmaceutical companies. Exploration of synergistic effects between different phytochemical components represents an underexplored area. This area of research has the potential to enhance therapeutic efficacy through systematic screening of compound combinations, investigation of complementary mechanisms of action, and assessment of pharmacokinetic interactions. Understanding synergies between *Sargassum*-derived compounds and conventional drugs offers potential for developing adjuvant therapies enabling dose reduction and minimization of adverse effects.

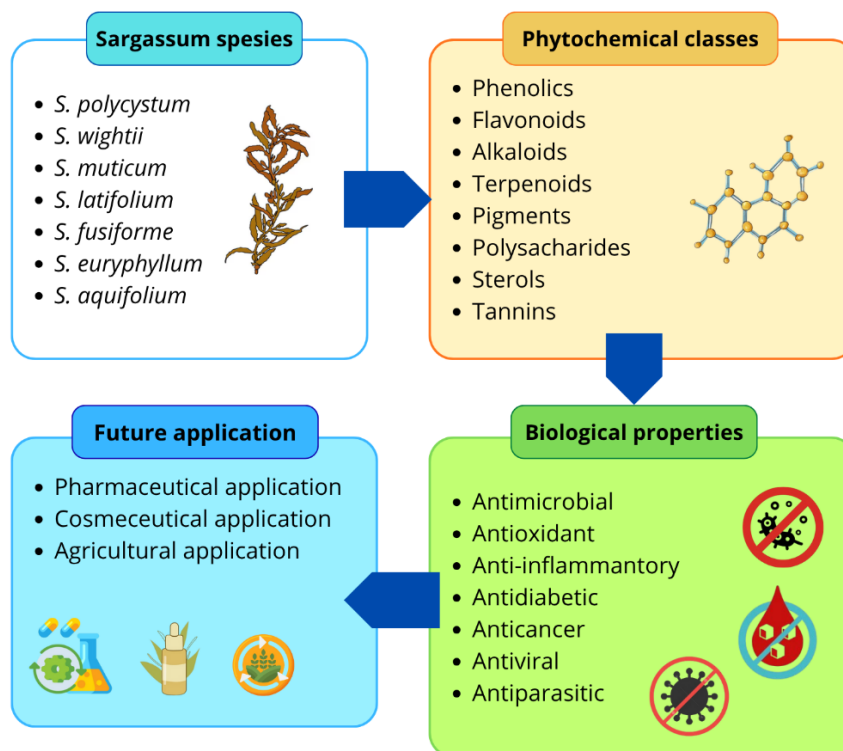


Figure 4. Summary of *Sargassum*-derived compounds, biological activities, and application potentials

6. Conclusions

This review demonstrates that the bioactive potential of *Sargassum* varies by species, phytochemical composition, and extraction method. Species such as *S. aquifolium*, *S. polycystum*, *S. fusiforme*, and *S. wightii* show particularly promising antioxidant, antimicrobial, antiviral, anticancer, and antidiabetic activities. To advance their application, standardized extraction and analytical protocols, systematic structure–activity investigations, and clinical and field validations are needed. Coordinated interdisciplinary efforts are essential to fully exploit these species for pharmaceutical, cosmeceutical, and agricultural innovation.

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8. Authors' Contributions

Nikman Azmin: Conceptualization, methodology, investigation, data curation, initial draft writing.

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9. Conflicts of Interest

The authors declare no conflicts of interest.

10. AI Declaration

The authors utilized ChatGPT and Claude to assist in data extraction and to enhance the clarity and coherence of the text. All content generated through these tools was thoroughly reviewed, revised, and validated by the authors, who assume full responsibility for the accuracy and conclusions of this publication.

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