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# BIOTECHNOLOGICAL APPLICATIONS AND THERAPEUTIC POTENTIAL OF *SARGASSUM* SPECIES: A REVIEW OF BIOACTIVE COMPOUNDS, TRANSLATIONAL OPPORTUNITIES, AND FUTURE PERSPECTIVES

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## ABSTRACT

*Sargassum* species represent a major but incompletely exploited source of biologically active compounds and renewable biomass. Interest in *Sargassum* has increased substantially because its biomass contains structurally diverse polysaccharides with potential pharmaceutical, nutraceutical, biomedical, environmental and industrial applications. This review critically synthesizes literature concerning the biotechnological and therapeutic potential of *Sargassum* species. Evidence indicates that *Sargassum fusiforme*, *Sargassum polycystum*, *Sargassum wightii*, *Sargassum horneri*, *Sargassum hemiphyllum*, *Sargassum muticum*, *Sargassum filipendula*, *Sargassum natans* and *Sargassum fluitans*, among others, differ substantially in chemical composition and therefore should not be treated as pharmacologically interchangeable resources. Fucoidan and other sulfated polysaccharides are among the most intensively investigated fractions and have demonstrated antioxidant, immunomodulatory, anti-inflammatory, antimicrobial, antiviral, anticoagulant and anticancer activities, although activity depends strongly on molecular weight, monosaccharide composition, sulfation pattern, extraction method and species origin. Alginate provides particularly important biotechnological value because of its biodegradability, biocompatibility and gel-forming capacity, supporting applications in hydrogels, wound dressings, tissue engineering and controlled drug delivery. *Sargassum* biomass also has potential as a biosorbent, biofertilizer feedstock, functional-feed ingredient and substrate for circular biorefineries. However, the translation of laboratory findings into approved therapeutics remains limited. Major barriers include inconsistent taxonomic identification, seasonal and geographic chemical variation, inadequate standardization of extracts, insufficient pharmacokinetic and toxicological information, limited controlled clinical trials and contamination risks associated with beach-cast biomass, particularly trace metals and arsenic. The review concludes that the greatest future opportunity lies in an integrated, species-resolved and quality-controlled biorefinery model in which high-value therapeutic compounds are recovered before residual biomass is converted into lower-value products. Progress toward clinical and commercial translation will require rigorous structure-function analysis, standardized extraction and characterization, relevant *in vivo* models, human studies and regulatory-quality contaminant control.

**Keywords:** *Sargassum*; Fucoidan; Alginate; Phlorotannins; Biotechnology; Therapeutics; Nutraceuticals; Drug Delivery; Biorefinery; Aquaculture; Bioremediation

## 1 INTRODUCTION

Marine macroalgae constitute an important reservoir of chemically diverse natural products and renewable biological materials. Among them, brown algae have attracted particular attention because their cell walls and associated tissues contain structurally complex polysaccharides and secondary metabolites that are uncommon in terrestrial plants [10]. The genus *Sargassum* is especially important because it includes numerous benthic and pelagic species distributed across tropical, subtropical and temperate marine ecosystems. Applied research has increasingly shifted from regarding *Sargassum* primarily as an ecological component of coastal ecosystems to recognizing it as a potential feedstock for pharmaceuticals, nutraceuticals, functional foods, biomaterials, environmental biotechnology and circular bioeconomy applications [12, 23, 24, 29].

Historically, several *Sargassum* species have been used as food and in traditional medicine [25, 28]. Modern phytochemical and pharmacological research has identified fucoidans, phlorotannins, meroterpenoids, sterols and related compounds as plausible contributors to the antioxidant, anti-inflammatory, antimicrobial, antiviral and anticancer activities reported for extracts and purified fractions. Nevertheless, traditional use should not be interpreted as direct evidence of clinical efficacy, because therapeutic activity depends on the chemical identity, concentration, purity, formulation, dose and biological availability of the active fraction [12].

The therapeutic importance of *Sargassum* cannot be understood independently of its biotechnology. Bioactivity begins with biomass selection and extends through extraction, purification, structural characterization, formulation and delivery [7, 28]. For example, the biological activity of fucoidan may vary according to molecular weight, degree and position of sulfation, monosaccharide composition and branching [2, 3, 8, 16, 17, 26, 27]. Similarly, alginate is not simply an inert industrial hydrocolloid: its mannuronic acid-to-guluronic acid composition affects viscosity, gel formation and suitability for biomedical formulations [1, 2, 6, 13, 23]. Consequently, a scientifically robust evaluation of *Sargassum* requires integration of taxonomy, chemistry, process engineering, pharmacology, toxicology and product development [12].

Recent research illustrates the breadth of this potential. Reviews of *S. fusiforme* describe polysaccharides, sterols, polyphenols and terpenes associated with antioxidant, anti-inflammatory, antitumor, antidiabetic, immunomodulatory, antimicrobial and anticoagulant activities. More recent work has also emphasized the importance of extraction technology and the need to establish clearer structure-function relationships for *Sargassum* polysaccharides [28, 31].

The genus also has growing environmental significance. Large accumulations of pelagic *Sargassum* in the tropical Atlantic and Caribbean have caused ecological and socioeconomic challenges, but they simultaneously represent a potentially substantial biomass resource [2, 15, 20]. Their sustainable use, however, requires careful contaminant monitoring because beach-cast or coastal-retained biomass may accumulate metals or arsenic. Therefore, biomass abundance alone cannot determine suitability for therapeutic, food or feed applications.

The present review critically examines the biotechnological and therapeutic potential of *Sargassum* species. Particular emphasis is placed on: (1) Taxonomic and ecological diversity among representative *Sargassum* species. (2) Major classes of bioactive compounds and their biological significance. (3) Therapeutic activities and proposed molecular mechanisms. (4) Biotechnology for extraction, purification and structural characterization. (5) Biomedical applications, including drug delivery and wound management. (6) Antimicrobial and therapeutic applications relevant to aquaculture and fish health. (7) Environmental biotechnology, biosorption and biorefinery development. (8) Safety, standardization, translational limitations and research priorities.

### 1.1 Conceptual Framework

The biotechnological and therapeutic value of *Sargassum* is determined by a chain of interacting processes rather than by biomass abundance alone (Figure 1). Species identity, habitat, seasonality and environmental conditions influence biomass chemistry [2, 15, 20]. Extraction and purification then determine which compounds are recovered, while structural characteristics influence biological activity and formulation potential. Translation into a therapeutic or biotechnology product subsequently requires efficacy, safety, reproducibility and quality control.

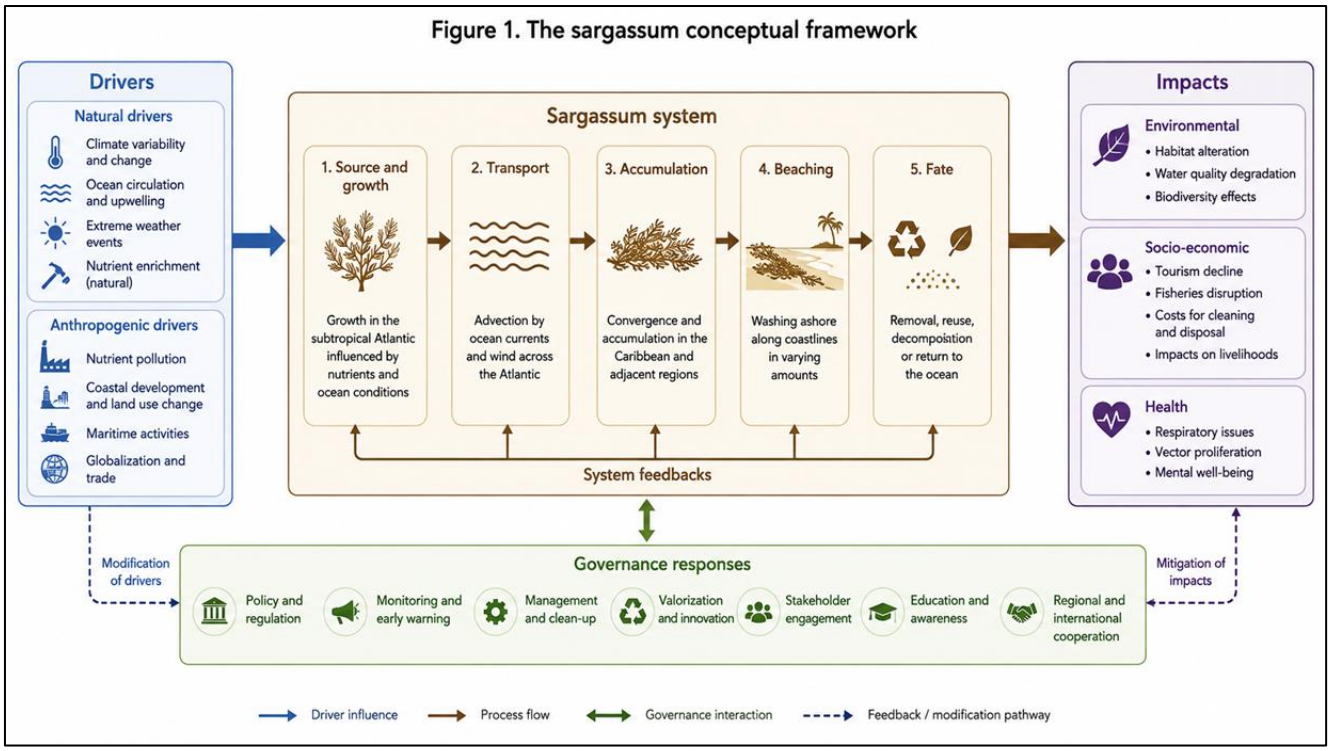


**Figure 1: Conceptual framework linking *Sargassum* resources, biomass chemistry, bioprocessing, high-value products, biotechnology and therapeutic translation**

## 2 MATERIALS AND METHODS

### 2.1 Search Strategy

A systematic thematic literature review was conducted using academic search engines, bibliographic databases, publisher platforms and open-access scientific repositories. The organization follows the general format of the attached review papers, which prioritize a transparent progression through search strategy, inclusion criteria, evidence synthesis, literature results, thematic discussion, knowledge gaps and conclusions.

Searches focused primarily on peer-reviewed literature published between 2020 and 2026 to capture recent developments in marine biotechnology, biomaterials, extraction technologies and therapeutic research. Earlier foundational publications were retained where necessary to establish the historical development of *Sargassum* pharmacology, identify original bioactive compounds or describe influential biological mechanisms.

Search terms included combinations of:

"*Sargassum* biotechnology," "*Sargassum* therapeutic potential," "*Sargassum* pharmacology," "*Sargassum* bioactive compounds," "fucoidan," "alginate," "laminaran," "phlorotannins," "meroterpenoids," "fucoxanthin," "*Sargassum* antioxidant," "*Sargassum* anti-inflammatory," "*Sargassum* antimicrobial," "*Sargassum* antiviral," "*Sargassum* anticancer," "*Sargassum* antidiabetic," "*Sargassum* immunomodulatory," "*Sargassum* drug delivery," "*Sargassum* wound dressing," "*Sargassum* biomaterials," "*Sargassum* aquaculture," "*Sargassum* fish health," "*Sargassum* bioremediation," "*Sargassum* biosorption," and "*Sargassum* biorefinery."

Species-specific searches included *S. fusiforme*, *S. polycystum*, *S. wightii*, *S. horneri*, *S. hemiphyllum*, *S. muticum*, *S. filipendula*, *S. natans* and *S. fluitans*.

### 2.2 Inclusion Criteria

Publications were considered relevant when they met one or more of the following criteria:

- Peer-reviewed studies or authoritative reviews addressing *Sargassum* chemistry, biotechnology or therapeutic potential.
- Research identifying *Sargassum* species and, where possible, bioactive compounds or purified fractions.

- Studies examining antioxidant, anti-inflammatory, antimicrobial, antiviral, anticancer, metabolic, immunomodulatory, neuroprotective or anticoagulant activities.
- Investigations involving extraction, purification, molecular characterization or structure-function relationships.
- Research concerning alginate, fucoidan, laminaran, polyphenols, phlorotannins, terpenoids, carotenoids or other relevant metabolites.
- Studies addressing biomedical materials, drug delivery, tissue engineering or wound management.
- Research examining environmental biotechnology, biosorption, bioremediation or integrated biorefinery systems.
- Aquaculture studies reporting effects of *Sargassum* biomass or extracts on fish growth, immunity, antioxidant status or disease resistance.
- Recent literature published principally between 2020 and 2026, supplemented with earlier foundational studies.
- Publications available in English.

### 2.3 Evidence Synthesis

The selected literature was grouped thematically into:

- Taxonomy and biomass diversity.
- Chemical composition and major bioactive fractions.
- Extraction and bioprocessing technologies.
- Antioxidant and anti-inflammatory activity.
- Antimicrobial and antiviral activity.
- Anticancer and antiproliferative potential.
- Metabolic, immunomodulatory and other therapeutic activities.
- Biomedical materials and drug delivery.
- Aquaculture and fish-health applications.
- Bioremediation and environmental biotechnology.
- Biorefinery and circular-economy applications.
- Safety, standardization and clinical translation.

Evidence was interpreted according to its level of biological validation. Thus, *in vitro* activity was distinguished from animal evidence and human clinical evidence. This distinction is particularly important because a compound that demonstrates cytotoxicity, antioxidant capacity or cytokine modulation under laboratory conditions cannot automatically be considered a clinically effective therapeutic.

## 3 RESULTS

Literature for this review was sourced from various academic search engines, bibliographic databases, publisher platforms, and open-access repositories, including Google Scholar, ResearchGate, Academia, Semantic Scholar, R Discovery, OiPub, ScienceDirect, PubMed/MEDLINE, SpringerLink, Web of Science, Scopus, Wiley Online Library, SciSpace, and institutional repositories. Reference lists of relevant review articles and primary research papers were also examined to identify additional literature relating to the biotechnological applications, bioactive compounds, pharmacological activities, therapeutic potential, and translational development of *Sargassum* species. The majority of journal articles were accessible through open-access platforms, publisher websites, institutional access, or other academic repositories. Where articles were identified through their Digital Object Identifiers (DOIs), the DOI was used to locate the original publication or an accessible version of the article.

An extensive collection of published literature was accumulated when the selected search terms were utilised. The searches focused on literature relating to *Sargassum* species diversity, chemical composition, bioactive compounds, extraction technologies, therapeutic activities, biomedical applications, environmental biotechnology, aquaculture applications, biorefinery development, safety, and translational challenges. The principal search categories were as follows:

- **Biotechnological applications of *Sargassum*:** Literature examining the use of *Sargassum* biomass and derived compounds in biotechnology, including biomaterials, pharmaceuticals, nutraceuticals, drug-delivery systems, aquaculture, agriculture, bioremediation, and circular biorefineries.
- **Bioactive compounds of *Sargassum*:** Studies investigating the chemical composition of *Sargassum* species and the occurrence of fucoidan, alginate, laminaran, phlorotannins, polyphenols, carotenoids, fucoxanthin, sterols, terpenoids, meroterpenoids, fatty acids, and other biologically relevant metabolites.

- ***Sargassum* polysaccharides:** Research examining the composition, extraction, purification, structural characteristics, and biological activities of fucoidan, alginate, laminaran, and other polysaccharides obtained from *Sargassum* species.
- **Extraction and bioprocessing technologies:** Studies evaluating conventional and emerging methods for recovering valuable compounds from *Sargassum*, including hot-water, acid, alkaline, solvent-based, ultrasound-assisted, microwave-assisted, enzyme-assisted, and other green extraction technologies.
- **Antioxidant activity of *Sargassum*:** Literature examining radical-scavenging capacity, reducing activity, modulation of oxidative stress, antioxidant enzymes, and the potential biological significance of antioxidant compounds and extracts.
- **Anti-inflammatory activity of *Sargassum*:** Studies investigating the effects of *Sargassum*-derived compounds on inflammatory mediators, cytokines, nitric oxide production, inducible nitric oxide synthase, cyclooxygenase-related pathways, NF-κB, MAPK, and other mechanisms associated with inflammation.
- **Antimicrobial and antiviral potential:** Research examining antibacterial, antifungal, antiviral, and other antimicrobial activities of *Sargassum* extracts, purified fractions, polysaccharides, phenolic compounds, and secondary metabolites.
- **Anticancer and antiproliferative potential:** Studies investigating the effects of *Sargassum*-derived compounds on cancer-cell proliferation, apoptosis, cell-cycle progression, oxidative stress, tumour-associated signalling pathways, and other mechanisms relevant to cancer research.
- **Metabolic and immunomodulatory activities:** Literature examining potential antidiabetic, lipid-modulating, immunomodulatory, anticoagulant, and other biological activities associated with *Sargassum* species and their bioactive compounds.
- **Biomedical materials and drug delivery:** Studies investigating alginate-, fucoidan-, and other *Sargassum*-derived materials for hydrogels, nanoparticles, microspheres, films, wound dressings, tissue-engineering scaffolds, encapsulation, and controlled or targeted drug delivery.
- ***Sargassum* in aquaculture and fish health:** Research examining the use of *Sargassum* biomass, extracts, polysaccharides, or fermented products in fish diets and their potential effects on growth, intestinal health, antioxidant responses, immunity, disease resistance, and aquaculture productivity.
- **Bioremediation and environmental biotechnology:** Studies investigating the ability of *Sargassum* biomass to adsorb, accumulate, or remove pollutants, including metals and other contaminants, and research examining the environmental applications of processed or residual biomass.
- ***Sargassum* biorefinery and biomass valorization:** Literature examining cascading approaches for the sequential recovery of high-value bioactive compounds and the subsequent utilization of residual biomass for biomaterials, biofertilizers, fermentation products, energy, and other applications.
- **Safety, standardization, and therapeutic translation:** Research addressing species authentication, chemical standardization, molecular characterization, contaminant screening, toxicology, pharmacokinetics, bioavailability, formulation, clinical evidence, regulatory requirements, and the progression of *Sargassum*-derived products from laboratory research to practical applications.

When searching Google Scholar and other academic databases for information on the biotechnological and therapeutic potential of *Sargassum* species, a substantial number of publications were retrieved across the different search categories. The literature included recent publications principally from 2020-2026, together with earlier foundational studies that were relevant to the discovery of important *Sargassum*-derived compounds, the characterization of polysaccharides, the identification of biological activities, and the development of biotechnology applications. The search results were subsequently refined according to publication relevance, subject area, year of publication, species investigated, compound or fraction studied, type of biological evidence, and the extent to which individual papers contributed to the objectives of the review.

The literature finally selected for the review included publications addressing several major dimensions of *Sargassum* biotechnology and therapeutic research. These consisted of studies identifying and characterizing bioactive compounds, investigations comparing the chemical composition and biological activities of different *Sargassum* species, and research examining the effects of geographic origin, seasonality, environmental conditions, and extraction procedures on biomass composition. Additional studies were selected because they provided information on the mechanisms underlying reported therapeutic activities, including oxidative stress, inflammation, microbial inhibition, immune regulation, apoptosis, cell proliferation, and metabolic processes.

The literature further demonstrated that research on *Sargassum* has expanded beyond the conventional investigation of crude extracts. A substantial proportion of more recent studies focused on the extraction, purification, fractionation, and structural characterization of specific compounds, particularly fucoidan, alginate, laminaran, and other polysaccharide fractions. These investigations were important because the reported biological properties of *Sargassum* may depend on molecular characteristics such as molecular weight, monosaccharide composition, sulfation pattern, degree of branching, purity, and the presence of associated compounds. Consequently, extracts or compounds obtained

from different *Sargassum* species, geographical regions, or extraction procedures were not considered chemically or biologically interchangeable.

However, not all papers retrieved for this review focused directly on therapeutic activity. Some publications concentrated primarily on the chemical composition and nutritional properties of *Sargassum* biomass, while others investigated extraction efficiency, purification methods, molecular structure, or process optimization. Several studies focused on environmental and industrial applications, including biosorption, bioremediation, biofertilizer production, fermentation, and bioenergy. These papers were considered relevant because they provided information concerning the broader biotechnological value of *Sargassum* and the potential for integrating therapeutic-product development into circular and cascading biorefinery systems.

Some publications focused specifically on biomedical applications of *Sargassum*-derived compounds. These included studies investigating alginate and fucoidan for the development of hydrogels, films, wound dressings, microspheres, nanoparticles, encapsulation systems, tissue-engineering materials, and controlled drug-delivery platforms. These studies were relevant because they demonstrated that the biotechnological value of *Sargassum* is not limited to the direct pharmacological activity of isolated compounds. Certain components may also function as biodegradable and biocompatible structural materials capable of improving the stability, delivery, retention, or controlled release of therapeutic substances.

The results also demonstrated considerable variation in the type and strength of evidence available for the reported therapeutic activities of *Sargassum*. A large proportion of studies consisted of *in vitro* experiments, including antioxidant assays, microbial inhibition tests, cancer-cell studies, enzyme assays, and investigations involving cultured immune or inflammatory cells. Other studies by Kumar *et al.* (2021) [10] and Zhang *et al.* (2025) [31], extended the investigation to *in vivo* models, providing information on biological activity, toxicity, disease mechanisms, immune responses, or therapeutic outcomes in whole organisms. Comparatively fewer studies had progressed to controlled clinical investigation. This distinction was considered important because evidence of activity in a chemical assay or cultured-cell system does not, by itself, establish therapeutic efficacy in humans.

The literature indicated that *Sargassum* species contain several major groups of compounds with potential biotechnological and therapeutic relevance. Polysaccharides, particularly fucoidan and alginate, represented among the most frequently investigated fractions [5, 9, 14, 30, 31]. Fucoidan was repeatedly associated with antioxidant, anti-inflammatory, immunomodulatory, antimicrobial, antiviral, anticoagulant, metabolic, and anticancer research [2, 3, 8, 16, 17, 26, 27], whereas alginate was particularly important for biomaterials, wound management, tissue engineering, and drug-delivery applications [1, 2, 6, 13, 23]. Laminaran and other neutral polysaccharides were also investigated for nutritional, antioxidant, and immunomodulatory applications [7, 10, 16, 18, 19, 24]. In addition, phlorotannins, polyphenols, carotenoids, terpenoids, meroterpenoids, sterols, and lipid-associated compounds contributed to the reported chemical and biological diversity of the genus [3, 10, 12].

The studies by Yende *et al.* (2014) [29], Saraswati *et al*. (2019) [22], Wang *et al.* (2023) [28], Zhang *et al.* (2020) [30], Torres-Narváez *et al.* (2025) [25] and Zhang *et al.* (2025) [31] further demonstrated that the therapeutic potential of *Sargassum* is distributed across several species rather than being represented by a single taxon. *Sargassum fusiforme* was among the most extensively investigated species and was frequently associated with studies of polysaccharides, antioxidant activity, anti-inflammatory effects, immunomodulation, metabolic activity, and nutraceutical applications. Other species, including *Sargassum polycystum*, *Sargassum wightii*, *Sargassum horneri*, *Sargassum hemiphyllum*, *Sargassum muticum*, *Sargassum filipendula*, *Sargassum natans*, and *Sargassum fluitans*, were also represented in the literature. However, the volume and type of evidence varied considerably among species.

A further major finding from studies by Zhang *et al.* (2020) [30] and Zhang *et al.* (2025) [31] was that the biological activity of *Sargassum*-derived products was influenced by factors extending beyond species identity. Geographic location, season of collection, environmental conditions, physiological state of the algae, biomass storage, pre-treatment, extraction procedures, and purification methods could all affect the chemical composition of the final product. This finding has important implications for the interpretation of therapeutic research because two extracts described broadly as originating from the same species may differ substantially in chemical composition and biological activity if they were collected or processed under different conditions [2].

The results also demonstrated increasing interest in the application of *Sargassum* within aquaculture and animal nutrition. Studies involving fish evaluated the use of whole, processed, extracted, or fermented *Sargassum* materials as functional dietary ingredients. The available literature examined effects on growth performance, intestinal condition, antioxidant responses, immune function, and resistance to pathogenic infection. Research involving species such as zebrafish (*Danio rerio*; Order Cypriniformes, Family Danionidae) and Nile tilapia (*Oreochromis niloticus*; Order Cichliformes, Family Cichlidae) provided evidence that selected *Sargassum*-derived materials may have applications

extending beyond human therapeutics. Nevertheless, the available studies differed in species, experimental design, *Sargassum* material, dosage, and measured responses, limiting direct comparison among investigations.

The literature relating to environmental biotechnology demonstrated a further dimension of *Sargassum* utilization. Biomass and processed materials have been investigated for their capacity to interact with pollutants and potentially function as biosorbents. In addition, the increasing availability of pelagic and beach-cast *Sargassum* has stimulated research into biomass valorization. However, the same environmental exposure that makes large quantities of biomass available may also create safety concerns because biomass can contain undesirable concentrations of arsenic, metals, salts, microorganisms, or other contaminants. Therefore, studies addressing contaminant screening were particularly relevant to determining whether specific biomass sources were suitable for pharmaceutical, nutraceutical, food, feed, agricultural, environmental, or other applications.

A major pattern emerging from the literature search was the increasing emphasis on integrated biorefinery approaches. Rather than considering *Sargassum* biomass solely as a source of one compound or one end product, several studies and reviews supported the sequential recovery of multiple fractions. High-value compounds and sensitive bioactive metabolites can potentially be recovered first, followed by polysaccharides and biomaterial components, while the remaining biomass may subsequently be investigated for fermentation, energy generation, agriculture, or other lower-value applications. This approach was particularly relevant to the conceptual framework developed for the present review because it links sustainable biomass sourcing and chemical characterization with cascading product recovery, quality control, therapeutic development, and circular-economy principles.

The results further revealed that the translation of *Sargassum* research from laboratory investigations to clinically or commercially established therapeutic products remains incomplete. Considerable evidence is available for antioxidant, anti-inflammatory, antimicrobial, antiviral, immunomodulatory, metabolic, and anticancer activities, but much of this evidence remains at the *in vitro* or preclinical stage. Important limitations identified across the literature included inconsistent taxonomic identification, variable extraction procedures, incomplete chemical characterization, limited information concerning pharmacokinetics and bioavailability, insufficient long-term toxicity studies, and a comparatively small number of controlled clinical trials.

A major finding from the literature search was therefore that the quantity of research available does not necessarily correspond to the level of translational evidence. Certain activities, particularly antioxidant and cytotoxic effects, were represented by numerous laboratory studies, whereas fewer investigations progressed through the complete sequence of standardized chemical characterization, mechanistic investigation, relevant *in vivo* evaluation, pharmacokinetic assessment, formulation development, clinical testing, and regulatory-quality assessment. This evidence gap formed the basis for the *Sargassum* Evidence-Translation Pathway presented in Figure 3.

Studies of *Sargassum* biotechnology were also not distributed evenly across all geographical regions or species. Considerable information was available for selected commercially important or historically studied species, particularly *S. fusiforme*, whereas substantially less information was available for many tropical, Caribbean, Atlantic, and developing-region species. Similarly, research involving pelagic *Sargassum*, including *S. natans* and *S. fluitans*, has increased because of recurrent biomass accumulations, but significant gaps remain concerning the standardization and safety of this biomass for high-value therapeutic applications.

Important research gaps were therefore identified concerning species-specific chemical variation, seasonal changes in bioactive compounds, standardized extraction procedures, structure-function relationships, bioavailability, pharmacokinetics, chronic toxicity, contaminant profiles, dosage optimization, long-term efficacy, interactions with other therapeutic compounds, and controlled human clinical studies. Additional gaps were identified in the scale-up of green extraction technologies, techno-economic evaluation of integrated biorefineries, life-cycle assessment, and the development of regulatory standards for *Sargassum*-derived pharmaceutical and biomedical products.

Therefore, although a substantial body of literature was identified, the final studies used in this review were selected based on their relevance to the central objective of understanding the biotechnological applications and therapeutic potential of *Sargassum* species. Particular attention was given to identifying the major bioactive compounds present, determining how these compounds are extracted and characterized, evaluating the biological activities reported across experimental systems, examining the development of biomedical and industrial applications, and identifying the scientific, safety, and regulatory requirements necessary for translating promising laboratory findings into safe and effective products. Information considered relevant from these papers was grouped thematically and synthesized in the subsequent sections of this review.

## 4 DISCUSSION

The literature demonstrates that *Sargassum* is a chemically and biologically heterogeneous resource (Table 1). The strongest concentration of evidence concerns *S. fusiforme* and its polysaccharides, although substantial research has also examined *S. polycystum*, *S. wightii*, *S. horneri*, *S. hemiphyllum*, *S. muticum* and *S. filipendula* [30, 31]. Across the literature, polysaccharides-particularly fucoidan, alginate and laminaran-were consistently identified as major components, accompanied by polyphenols, phlorotannins, sterols, terpenoids and pigments [2].

Recent reviews of *S. fusiforme* consistently identify alginate, fucoidan and laminaran as major polysaccharide fractions and report a broad range of biological activities. Extraction approaches now include conventional hot-water, acid and alkaline procedures as well as ultrasound-, microwave- and enzyme-assisted techniques. However, the literature repeatedly emphasizes that extraction conditions can alter molecular characteristics and therefore influence apparent biological activity [31].

The results also indicated a methodological transition from crude-extract screening toward fractionation, structural characterization and engineered formulations. For example, purified fucoidan fractions from *S. polycystum* have demonstrated antibacterial, antioxidant and anticancer activities, whereas contemporary biotechnology increasingly investigates fucoidan- and alginate-based nanoparticles, hydrogels and other controlled-delivery systems [16, 17, 27].

A further result was the expansion of *Sargassum* biotechnology beyond human therapeutics. Previous research has investigated its use in fish diets and disease resistance, biosorption of pollutants and integrated biorefineries. For example, fermented *S. muticum* supplementation has been associated with improved growth, intestinal health, antioxidant and immune responses and resistance to bacterial infection in Nile tilapia [18].

**Table 1: *Sargassum* species and their reported biotechnological and therapeutic significance**

| Species | Order / Family | Major compounds reported | Representative potential applications | Key literature |
|---|---|---|---|---|
| *Sargassum fusiforme* | Fucales / Sargassaceae | Fucoidan, alginate, laminaran, polyphenols, sterols, terpenes | Antioxidant, anti-inflammatory, antitumor, antidiabetic, immunomodulatory, nutraceutical and functional-food applications | Wang *et al*. (2023) [28]; Zhang *et al.* (2020, 2025) [30, 31] |
| *Sargassum polycystum* | Fucales / Sargassaceae | Fucoidan and sulfated polysaccharides | Antioxidant, antibacterial and anticancer research | Palanisamy *et al.* (2018, 2019) [16, 17] |
| *Sargassum wightii* | Fucales / Sargassaceae | Sulfated polysaccharides, fucoidan, phenolics | Anti-inflammatory and antioxidant applications | Saraswati *et al.* (2019) [22] |
| *Sargassum horneri* | Fucales / Sargassaceae | Fucose-rich sulfated polysaccharides | Anti-inflammatory and antiviral research | Hoshino *et al.* (1998) [9]; Saraswati *et al.* (2019) [22] |
| *Sargassum hemiphyllum* | Fucales / Sargassaceae | Low-molecular-weight fucoidan | Immunomodulatory and adjunct therapeutic research | Liu *et al.* (2012) [12]; Tsai *et al.* (2017) [26] |
| *Sargassum muticum* | Fucales / Sargassaceae | Polysaccharides, phenolics and dietary bioactives | Functional feeds, fish immunity and circular biomass utilization | Radwan *et al.* (2025) [18] |
| *Sargassum filipendula* | Fucales / Sargassaceae | Fucoidan, carotenoids, phenols and phlorotannins | Pharmaceutical, nutraceutical and food applications | Zhang *et al*., (2025) [31] |
| *Sargassum natans* | Fucales / Sargassaceae | Alginate, polysaccharides and minerals | Pelagic biomass valorization and environmental biotechnology | (Palanisamy *et al.* (2018, 2019) [16, 17]; Venkatesan *et al*. (2022) [27] |

| | | | | |
|---|---|---|---|---|
| *Sargassum fluitans* | Fucales / Sargassaceae | Polysaccharides and associated metabolites | Biomass valorization, biosorption and biorefinery applications | Radwan *et al*., (2025) [18] |

### 4.1 Chemical Diversity as the Foundation of Biotechnology

The principal reason *Sargassum* has attracted sustained biotechnological interest is its chemical diversity (Table 2). Brown algal cell walls provide a matrix rich in polysaccharides, particularly alginate and sulfated fucose-containing polymers collectively described as fucoidans. Storage glucans such as laminaran and structurally diverse phenolic, terpenoid and pigment fractions add further value.

### 4.2 Fucoidan

Fucoidan is among the most intensively studied *Sargassum*-derived bioactive fractions. It is generally characterized as a sulfated, fucose-rich heteropolysaccharide, but its structure differs substantially among species and extraction conditions. Minor monosaccharides may include galactose, mannose, xylose, rhamnose, glucose and uronic acids. Consequently, "fucoidan" should be regarded as a chemically heterogeneous family rather than a single standardized molecule [2, 3, 8, 16, 17, 26, 27].

Its reported activities include antioxidant, anti-inflammatory, immunomodulatory, anticoagulant, antiviral and anticancer effects. However, molecular weight and sulfation are particularly important determinants of activity. The same biological name applied to fractions isolated from different species does not guarantee equivalent pharmacological behavior [30, 31].

### 4.3 Alginate

Alginate is a linear polysaccharide composed principally of β-D-mannuronic acid and α-L-guluronic acid residues. Its major technological advantage is its ability to form gels and viscous matrices under suitable ionic conditions. These properties make alginate particularly useful in hydrogels, films, beads, microspheres, wound dressings and controlled-release systems [1, 2, 6, 13, 23].

Although alginate is widely obtained from brown algae rather than exclusively from *Sargassum*. *Sargassum* biomass can provide an important source. Its biocompatibility, biodegradability and capacity to retain water make it especially valuable for biomedical engineering. Modern reviews describe alginate-based systems for wound healing and drug delivery, while clinical and preclinical evidence supports the usefulness of alginate-containing dressings for exudative wounds and tissue repair [1, 13].

### 4.4 Laminaran, Phenolics and Phlorotannins

Laminaran is a β-glucan storage polysaccharide and contributes to the nutritional and potential immunological value of brown algae. Phenolics and phlorotannins provide an additional class of compounds associated with radical scavenging, metal-chelating and inflammation-modulating effects. Phlorotannins are of particular interest because they are characteristic polyphenolic metabolites of brown algae [3, 10, 12].

### 4.5 Terpenoids, Meroterpenoids and Pigments

*Sargassum* also produces lipophilic secondary metabolites, including terpenoids and meroterpenoids, which have attracted attention in antimicrobial and anticancer research. Fucoxanthin and related carotenoids contribute to antioxidant activity and may have metabolic and anti-inflammatory relevance. The coexistence of water-soluble and lipid-soluble fractions strengthens the rationale for sequential extraction rather than a single crude-extraction approach [3, 10, 12].

**Table 2: *Sargassum*-derived compounds and their biotechnology relevance**

| Compound class | Representative constituents | Principal technological properties | Reported biological potential | Important limitations | References (Authors & Year) |
|---|---|---|---|---|---|
| Sulfated polysaccharides | Fucoidan | Anionic, water-soluble, biodegradable and bioactive polysaccharide; structural versatility supports formulation into films, hydrogels, nanoparticles and other delivery systems | Antioxidant, anti-inflammatory, antiviral, anticoagulant, immunomodulatory and anticancer potential | Considerable variation in molecular weight, sulfation pattern, monosaccharide composition and biological activity among species, locations and extraction procedures | Zhang *et al.* (2020) [30]; Anjana & Arunkumar (2024) [2]; Fonseca-Barahona *et al.* (2025) [7] |
| Alginates | Mannuronic acid (M) and guluronic acid (G) polymers | Strong gel-forming capacity, water absorption, viscosity modification, biocompatibility and biodegradability; suitable for hydrogels, wound dressings, encapsulation and controlled drug delivery | Applications in wound management, tissue engineering, cell encapsulation and drug-delivery systems | Functional properties depend substantially on the M/G ratio, molecular weight, polymer composition and degree of purification | Zhang *et al.* (2020) [30]; Anjana & Arunkumar (2024) [2]; Fonseca-Barahona *et al*. (2025) [7] |
| Storage glucans | Laminaran (laminarin) | Soluble β-glucan with potential use as a functional-food ingredient and bioactive polysaccharide | Antioxidant, immunomodulatory, metabolic and other health-related activities | Comparatively limited clinical validation; biological activity may vary according to molecular structure, source and extraction method | Zhang *et al.* (2020) [30]; Fonseca-Barahona *et al.* (2025) [7] |
| Phlorotannins | Brown-algal polyphenols, including phloroglucinol-derived oligomers and polymers | Strong antioxidant and reducing capacity; metal-chelating potential; possible application as natural functional ingredients and bioactive components | Antioxidant, anti-inflammatory, antimicrobial and antiproliferative potential | Chemical instability, susceptibility to oxidation and limited bioavailability may restrict direct therapeutic translation | Saraswati *et al.* (2019) [22]; Fonseca-Barahona *et al.* (2025) [7] |
| Carotenoids | Fucoxanthin and related derivatives | Natural pigment with antioxidant properties; | Antioxidant, anti-inflammatory and metabolic activities, | Sensitive to light, heat and oxidation; | Saraswati *et al.* (2019) [22]; |

| | | | | | |
|---|---|---|---|---|---|
| | | potential application in nutraceuticals, functional foods and sequential biorefinery processes | with additional potential health-related applications | stability during extraction, processing and storage is an important limitation | Anjana & Arunkumar (2024) [2]; Fonseca-Barahona *et al.* (2025) [7] |
| Terpenoids and meroterpenoids | Sargaquinoic acid, sargachromenol, sargahydroquinoic acid and related compounds | Structurally diverse secondary metabolites with potential value as specialized pharmaceutical and biotechnological lead compounds | Antimicrobial, anti-inflammatory, neuroprotective and anticancer activities reported in experimental studies | Often occur in relatively low or variable concentrations; isolation, purification, structural characterization and large-scale production remain challenging | Yende *et al.* (2014) [29]; Saraswati *et al.* (2019) [22] |
| Sterols and lipids | Fucosterol, polyunsaturated fatty acids and other lipid-associated compounds | Lipophilic bioactive components with potential applications in nutraceutical, functional-food and pharmaceutical formulations | Antioxidant, anti-inflammatory, antimicrobial and metabolic activities; selected compounds, including fucosterol, have also been investigated for other therapeutic effects | Lipid composition may vary substantially among species and environmental conditions, while oxidation and stability can affect product quality | Yende *et al.* (2014) [29]; Saraswati *et al.* (2019) [22]; Fonseca-Barahona *et al.* (2025) [7] |

Note: The biological activities presented in this Table 2 summarize reported experimental and preclinical potential and should not be interpreted as evidence of established clinical efficacy. The chemical composition and biological activity of *Sargassum*-derived materials may vary according to species identity, geographic origin, season, environmental conditions, biomass handling, extraction procedures, purification and molecular characteristics. This is particularly important for fucoidan and other structurally heterogeneous polysaccharides.

### 4.6 Extraction Technologies and Structure-Function Relationships

The chemical composition of polysaccharides from SF varies depending on the measurement method and extraction purification processes chosen by the researcher. Of course, the environment, source, and harvesting season of SF may also fluctuate the measurement results. Seasonal changes can affect the growth and metabolic processes of seaweed, leading to fluctuations in the polysaccharide composition [31]. Different techniques for extracting bioactive compounds from *Sargassum* exist and are utilized, but selecting the right method for extraction, isolation, and purification is important when considering yield and impurity of the final product [10, 31].

However, more advanced techniques are still needed to explore the detailed structural characterization of polysaccharides, particularly the conformational changes of sugar chains, the types of linkage groups, and the mechanisms of interaction with target tissues *in vivo*. In the future, deeper research on the structure of SFPs should be strengthened, and a more comprehensive structural analysis should be carried out through a variety of modern analytical techniques, so as to clarify the correspondence between key active groups and biological functions [10, 31].

Conventional extraction of *Sargassum* compounds has relied on hot water, dilute acids, alkalis and organic solvents. These methods remain important but may require substantial energy, chemical inputs or processing time. Newer approaches include ultrasound-assisted extraction, microwave-assisted extraction and enzyme-assisted extraction [2, 31].

The major biotechnological challenge is not simply maximizing extraction yield. A high yield may not represent a high-quality therapeutic fraction. Harsh acid or alkaline conditions can alter molecular weight, hydrolyze susceptible structures or modify sulfation patterns. Therefore, optimization should simultaneously evaluate yield, purity, structural integrity, energy consumption, solvent requirements and biological activity.

This principle is particularly evident for *S. fusiforme* polysaccharides, where recent literature compares conventional and assisted extraction approaches while emphasizing the need to understand relationships among extraction conditions, chemical structure and biological function [31].

#### 4.6.1 Antioxidant Potential

Antioxidant activity is one of the most frequently reported properties of *Sargassum* extracts. Assays such as DPPH, ABTS, ferric reducing capacity and hydroxyl-radical scavenging are useful for preliminary screening, but chemical antioxidant capacity should not automatically be equated with therapeutic efficacy in living organisms [7, 16, 18, 24].

The biological relevance of antioxidant fractions depends on absorption, metabolism, distribution and interaction with endogenous antioxidant systems. Therefore, stronger evidence comes from studies demonstrating effects on oxidative biomarkers, antioxidant enzymes, inflammatory pathways or disease models.

A fucoidan fraction from *S. polycystum* demonstrated dose-dependent antioxidant activity and was subsequently associated with cytotoxic and apoptosis-related effects in breast and colon cancer cell lines. Such findings support the value of purified fractions but remain primarily preclinical evidence rather than proof of therapeutic efficacy in humans [16].

#### 4.6.2 Anti-Inflammatory Potential

Chronic inflammation contributes to the development and progression of cardiovascular disease, metabolic disorders, cancer and other chronic conditions. Consequently, anti-inflammatory *Sargassum* compounds have received considerable attention.

Evidence includes suppression of nitric oxide production, reduced expression of inducible nitric oxide synthase, modulation of cytokines and interference with NF-κB and mitogen-activated protein kinase signaling. Reviews of *Sargassum* sulfated polysaccharides identify effects involving TNF-α, IL-1β, IL-6, COX-2 and other inflammatory mediators [10].

Studies involving *S. wightii*, *S. horneri* and related species indicate that sulfated polysaccharides and other polar and nonpolar metabolites can modify inflammatory responses. However, the evidence remains heterogeneous because studies differ in species identity, extraction methods, dose and biological models [7, 10, 22].

The anti-inflammatory potential of *Sargassum* should therefore be interpreted mechanistically rather than generically. A crude extract with multiple metabolites may act differently from a purified fucoidan or phlorotannin fraction. Future studies should identify molecular targets and evaluate whether concentrations effective *in vitro* can be achieved safely *in vivo* [10, 31].

### 4.7 Antimicrobial and Antiviral Activity

#### 4.7.1 Antibacterial Activity

Several *Sargassum* extracts and polysaccharide fractions demonstrate antibacterial activity. A notable example is Fu-F2, a fucoidan fraction from *S. polycystum*, which demonstrated antibacterial activity against tested pathogens and was subsequently evaluated *in vivo* using zebrafish. The study illustrates the value of progressing beyond agar-based antimicrobial screening toward organism-level evaluation [17].

Possible antibacterial mechanisms include disruption of membrane integrity, altered permeability, oxidative effects and interference with microbial surface interactions. Nevertheless, many published studies remain preliminary and require comparison with established antimicrobial agents and resistance-oriented testing.

#### 4.7.2 Antiviral Activity

Sulfated polysaccharides are of interest because negatively charged sulfate groups may interfere with viral attachment, adsorption or other stages of infection. A sulfated polysaccharide isolated from *S. horneri* demonstrated antiviral activity against herpes simplex virus type 1, human cytomegalovirus and HIV-1 in experimental systems, illustrating the potential importance of sulfated structures in antiviral biotechnology [9].

However, antiviral activity in cultured cells is not equivalent to clinical antiviral efficacy. Translation requires pharmacokinetic studies, toxicity assessment, relevant animal models and controlled human trials.

### 4.7.3 Anticancer and Antiproliferative Potential

The anticancer literature by Tsai *et al.* (2017) [26], Palanisamy *et al*. (2019) [17] and Fonseca-Barahona *et al.* (2025) [7] on *Sargassum* includes crude extracts, purified polysaccharides, phlorotannins, carotenoids and terpenoid-rich fractions. Proposed mechanisms include:

- Induction of apoptosis.
- Cell-cycle arrest.
- Modulation of oxidative stress.
- Suppression of inflammatory signaling.
- Inhibition of proliferation-related pathways.
- Reduced migration or invasion in experimental models.
- Modulation of PI3K/Akt, MAPK and NF-κB-associated pathways.

For *S. polycystum*, purified fucoidan fractions have demonstrated cytotoxicity against MCF-7 breast cancer and HCT-15 colon cancer cells, with evidence consistent with apoptosis *in vitro* [16]. These findings are scientifically important but must not be interpreted as evidence that *S. polycystum* is a clinically established cancer treatment.

A significant translational distinction is that one controlled clinical trial evaluated low-molecular-weight fucoidan derived from *S. hemiphyllum* as supplemental therapy in patients with metastatic colorectal cancer. The existence of this randomized clinical investigation is important because it demonstrates progression beyond cell and animal studies, although the broader clinical evidence base remains limited and insufficient to establish generalized anticancer efficacy for *Sargassum* products [26].

Thus, the current evidence on Table 3 supports continued development of *Sargassum*-derived compounds as potential adjuncts, drug leads or delivery materials, but not their unqualified substitution for evidence-based oncology.

**Table 3: Therapeutic activities of *Sargassum* species and evidence interpretation**

| Activity | Representative species / fraction | Experimental evidence | Proposed mechanisms | Evidence status | Key literature |
|---|---|---|---|---|---|
| Antioxidant | *S. fusiforme* polysaccharides | Chemical and biological models | Radical scavenging; modulation of oxidative processes | Predominantly preclinical | Wang *et al.* (2023) [28]; Zhang *et al.* (2025) [31] |
| Anti-inflammatory | *S. wightii*, *S. horneri* polysaccharides | Cell and animal models | Reduced NO, cytokines and inflammatory signaling | Preclinical | Saraswati *et al.* (2019) [22] |
| Antibacterial | *S. polycystum* Fu-F2 | *In vitro* and zebrafish study | Membrane-associated and oxidative mechanisms proposed | Preclinical | Palanisamy *et al.* (2019) [17] |
| Antiviral | *S. horneri* sulfated polysaccharide | Cell-based viral assays | Interference with viral attachment/penetration and later stages | Preclinical | Hoshino *et al.* (1998) [9] |
| Anticancer | *S. polycystum* fucoidan | Human cancer-cell lines | Apoptosis and antiproliferative effects | *In vitro* | Palanisamy *et al.* (2018) [16] |
| Adjunct cancer therapy | Low-molecular-weight fucoidan from *S. hemiphyllum* | Randomized clinical study | Adjunct biological and therapeutic effects investigated | Limited human evidence | Tsai *et al.* (2017) [26] |

| | | | | | |
|---|---|---|---|---|---|
| Antidiabetic/metabolic | Mainly *S. fusiforme* fractions | Cell and animal studies | Effects on glucose and lipid metabolism | Predominantly preclinical | Wang *et al.* (2023) [28] |
| Immunomodulatory | *S. fusiforme* polysaccharides and other fractions | Experimental models | Modulation of cytokines and immune responses | Preclinical | Zhang *et al.* (2020, 2025) [30, 31] |
| Neuroprotective potential | Selected meroterpenoid and phenolic fractions | Experimental studies | Antioxidant and signaling modulation | Early-stage | Liu *et al.* (2012) [12] |

Critical interpretation: Most reported activities remain at the *in vitro* or animal stage. "Therapeutic potential" should therefore be interpreted as a research and development opportunity rather than confirmation of clinical efficacy.

#### 4.7.4 Metabolic, Antidiabetic and Immunomodulatory Applications

*Sargassum* research increasingly addresses chronic metabolic disease. Polysaccharides and other fractions have been investigated for effects on glucose regulation, lipid metabolism, oxidative stress and inflammation.

The broad composition of *S. fusiforme* makes it especially prominent in this area. Reviews report antioxidant, antidiabetic, immunomodulatory and anticoagulant activities among its investigated biological effects [28, 30].

Possible mechanisms include inhibition of carbohydrate-processing enzymes, improved oxidative status, reduced inflammatory signaling, modulation of gut microbiota and effects on lipid metabolism. However, the relative importance of individual compounds remains incompletely resolved. A whole extract may produce different effects from purified fucoidan because multiple constituents can interact.

#### 4.7.5 Biomedical Materials and Drug Delivery

One of the strongest biotechnological opportunities associated with *Sargassum* is the use of its polysaccharides as structural biomaterials.

#### 4.7.6 Alginate-Based Materials

Alginate can absorb exudate, form hydrogels and maintain a moist environment. These characteristics make alginate attractive for wound management. It can be engineered into films, fibers, foams, wafers, beads and composite hydrogels.

Modern biomedical reviews emphasize that alginate materials can support tissue repair, wound closure and drug incorporation. Their performance can be enhanced by combining alginate with antimicrobial compounds, nanoparticles, antioxidants or other bioactive materials [1, 13].

#### 4.7.7 Fucoidan-Based Nanotechnology

Fucoidan is also being investigated as a functional material for nanoparticles and controlled-delivery systems. Fucoidan-based nanoparticles may be produced through approaches including self-assembly, precipitation, emulsification, ultrasonication and green synthesis. Proposed applications include cancer therapy, antimicrobial delivery, tissue engineering and diagnostic imaging.

The significance of these systems is twofold. First, fucoidan may possess intrinsic biological activity. Second, it can act as part of a carrier system for other drugs. Therefore, biotechnology can potentially combine the biological properties of the marine polysaccharide with improved delivery of an established therapeutic compound [27].

Recent reviews specifically examining *Sargassum* polysaccharides also identify nanoparticles, hydrogels, micelles, vesicles, films and fibers as promising platforms for controlled and targeted drug delivery [5]. Table 4 presents the major biotechnological applications of *Sargassum* biomass.

**Table 4: Biotechnological applications of *Sargassum* biomass**

| Application | Principal *Sargassum*-derived resource | Biotechnology principle | Potential products | References |
|---|---|---|---|---|
| Nutraceuticals and functional foods | Fucoidan, polyphenols, phlorotannins, carotenoids, fucoxanthin, sterols and other bioactive metabolites | Extraction, purification, chemical characterization and standardized formulation of biologically active fractions for incorporation into foods and supplements | Functional foods, dietary supplements, nutraceutical ingredients and antioxidant formulations | Liu *et al.* (2020) [11]; Torres-Narváez *et al.* (2025) [25]; Nagarajan *et al.* (2026) [15] |
| Pharmaceutical discovery | Fucoidan, phlorotannins, terpenoids, meroterpenoids, sterols and other secondary metabolites | Bioassay-guided extraction and fractionation followed by compound isolation, structural characterization and biological screening | Pharmaceutical lead compounds, bioactive fractions and potential adjunct therapeutic agents | Liu *et al*. (2020) [11]; Haggag *et al.* (2023) [8]; Torres-Narváez *et al.* (2025) [25] |
| Drug delivery | Alginate, fucoidan and other *Sargassum*-derived polysaccharides | Gelation, ionic cross-linking, encapsulation, nanoparticle formation and controlled-release technologies | Nanoparticles, nanospheres, hydrogels, beads, microspheres, films and other controlled or targeted drug-delivery systems | Haggag *et al.* (2023) [8]; Bora *et al.* (2026) [3]; Cheong *et al.* (2026) [5] |
| Wound management | Primarily alginate; potentially alginate-based composites incorporating other bioactive *Sargassum* fractions | High fluid absorption, hydrogel formation, maintenance of a moist wound environment and incorporation of therapeutic agents | Wound dressings, hydrogels, absorbent pads, composite films and bioactive wound-care materials | da Silva *et al.* (2024) [6]; Mazurek *et al.* (2025) [13]; Shi *et al.* (2026) [23] |
| Tissue engineering and regenerative biomaterials | Alginate and fucoidan; alginate/fucoidan composite materials | Biocompatible and biodegradable scaffold formation, hydrogel engineering and encapsulation of cells or therapeutic compounds | Cell-supporting matrices, injectable hydrogels, tissue-engineering scaffolds and regenerative biomaterials | Haggag *et al.* (2023) [8]; Mazurek *et al.* (2025) [13]; Cheong *et al.* (2026) [5] |
| Aquaculture and functional feeds | Whole *Sargassum* biomass, seaweed meal, polysaccharides, polyphenols and other extracts | Functional feed supplementation aimed at improving nutrition, antioxidant status, immunity, intestinal function and disease resistance | Functional aquafeeds, immunostimulatory feed additives and antioxidant supplements | Siddik *et al.* (2023) [24]; Nagarajan *et al.* (2026) [15] |
| Bioremediation and wastewater treatment | Whole, dried, processed or immobilized *Sargassum* biomass; alginate-containing cell-wall material | Biosorption, ion exchange, complexation and bioaccumulation of contaminants from aqueous systems | Biosorbents for wastewater treatment, metal-removal systems and pollutant-remediation materials | Saldarriaga-Hernandez *et al.* (2020) [20]; Carreira *et al.* (2023) [4]; Salimi *et al.* (2025) |
| Integrated biorefinery and biomass valorization | Whole biomass, including sequentially recovered fucoidan, alginate, laminarin, polyphenols, pigments | Cascading extraction and fractionation of high-value and lower-value products to maximize biomass | Pharmaceuticals, nutraceuticals, biomaterials, biofertilizers, compost, | Liu *et al.* (2020) [11]; Nagarajan *et al.* (2026) [15] |

| | | | | |
|---|---|---|---|---|
| | and residual carbohydrates | utilization and reduce waste | bioethanol, biogas and other bioproducts | |

### 4.8 Aquaculture and Fish-Health Applications

The therapeutic and biotechnology potential of *Sargassum* extends to aquaculture (Table 5). Fish feeds containing marine algal biomass or fermented products may provide polysaccharides, antioxidants and other compounds capable of modifying gut health, oxidative status and immune function.

This field is particularly relevant because the user requirement for species-specific evidence should include taxonomic information where fish are involved. Available studies illustrate both direct therapeutic testing and dietary supplementation.

**Table 5: *Sargassum* biotechnology and therapeutic applications in aquaculture/fish studies**

| Fish species | Scientific name | Order | Family | *Sargassum* material | Principal reported outcome | Reference |
|---|---|---|---|---|---|---|
| Zebrafish | *Danio rerio* | Cypriniformes | Danionidae | Fu-F2 fucoidan fraction from *S. polycystum* | Improved survival and antioxidant-related responses in experimental bacterial-infection research | Palanisamy *et al.* (2019) [17] |
| Nile tilapia | *Oreochromis niloticus* | Cichliformes | Cichlidae | Fermented *S. muticum* in diet | Improved growth, intestinal health and immune-antioxidant responses; improved resistance to *Aeromonas hydrophila* | Radwan *et al.* (2025) [18] |

The *S. polycystum* study involving *D. rerio* is important because it incorporated both *in vitro* antibacterial testing and *in vivo* evaluation (Table 5). This approach provides stronger biological evidence than antimicrobial screening alone. Nevertheless, findings from zebrafish cannot automatically be generalized to commercially cultured fish species or to human therapeutics [17].

Similarly, dietary fermented *S. muticum* has demonstrated potential as a functional-feed ingredient for Nile tilapia (Table 5). Reported outcomes included improved growth, intestinal health, antioxidant and immune responses and greater resistance to bacterial infection. This provides a promising example of marine biomass biotechnology in which processing through fermentation may improve biological utilization of algal materials [18].

Future aquaculture research could possibly compare:

- Whole versus extracted biomass.
- Raw versus fermented *Sargassum*.
- Species-specific optimal inclusion levels.
- Digestibility and nutrient availability.
- Long-term effects on growth and reproduction.
- Immune mechanisms.
- Pathogen-specific disease resistance.
- Potential accumulation of arsenic or metals.

Undertaking these studies could possibly help answer other research questions in aquaculture to better understand more about which Sargassum species can be used most effectively and what benefits could be derived [14, 19].

#### 4.8.1 Bioremediation and Environmental Biotechnology

*Sargassum* biomass can interact with dissolved contaminants through adsorption, ion exchange, complexation and other physicochemical processes. Its cell-wall chemistry and high surface area make it potentially useful as a biosorbent for metals and other pollutants.

A circular-economy review of *Sargassum* biotechnology emphasizes that environmental decontamination and biomass valorization can potentially be integrated. Pollutant uptake, however, creates an important trade-off: biomass used to capture contaminants may no longer be suitable for food, feed or therapeutic applications. Therefore, a sustainable biorefinery must segregate biomass streams according to intended use and contamination status [20].

This distinction is critical for beach-cast Atlantic *Sargassum*. Recent research indicates that trace-element concentrations can change during coastal retention, and different elements may exhibit different accumulation or loss patterns. Such variability reinforces the need for contaminant screening before pharmaceutical, nutraceutical or agricultural utilization.

### 4.8.2 Integrated Biorefinery Development

A single-product approach is unlikely to maximize the economic value of *Sargassum*. For example, using all biomass exclusively for biofuel could waste high-value compounds, whereas extracting only fucoidan could leave substantial residual biomass.

A cascading biorefinery model is therefore preferable:

Biomass authentication and screening → washing and stabilization → recovery of sensitive high-value metabolites → polysaccharide extraction → alginate recovery → biomaterial or pharmaceutical formulation → fermentation/energy recovery from residual fractions → fertilizer or other low-value applications where contamination status permits

This approach (Figure 2) can improve resource efficiency and reduce waste. Techno-economic studies and recent biorefinery reviews increasingly support the recovery of multiple products, particularly alginate and fucoidan, before conversion of residual material into lower-value products.

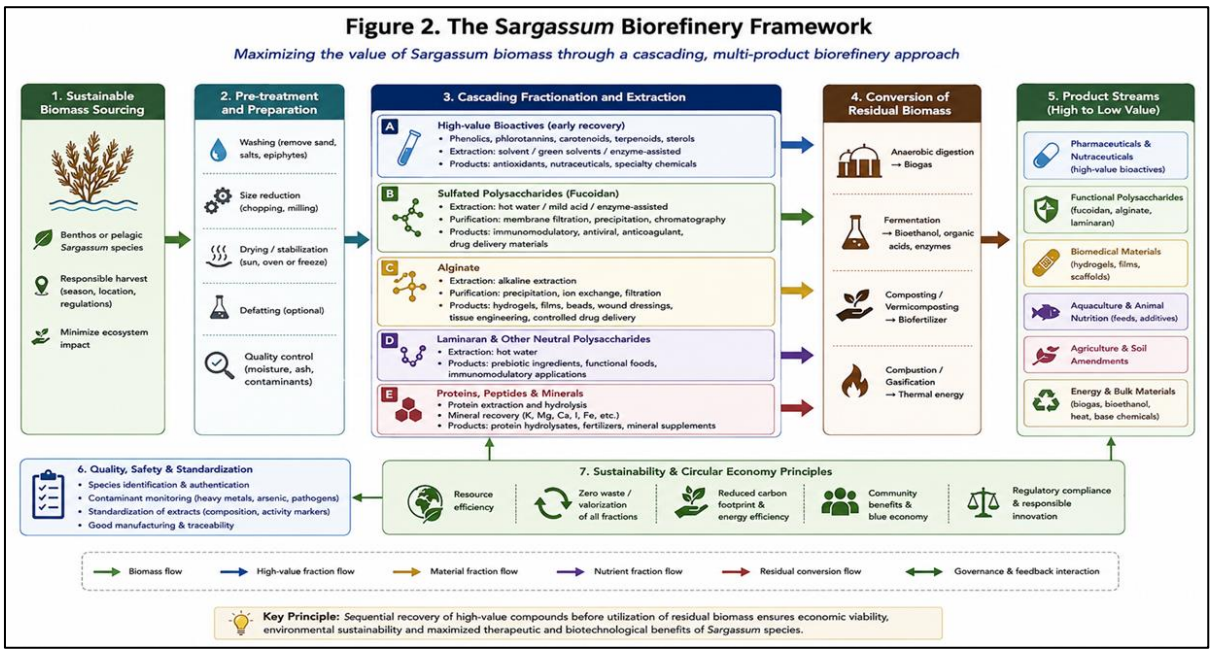


**Figure 2: Integrated *Sargassum* biorefinery and cascading valorization framework.**

### 4.8.3 Safety, Quality Control and Translational Challenges

The major limitation in *Sargassum* therapeutic research is not the absence of promising compounds. Rather, it is the gap between promising preclinical findings and reproducible, regulated therapeutic products.

#### 4.8.3.1 Species Authentication

Misidentification or inconsistent nomenclature can undermine reproducibility. Chemical composition may differ among closely related or geographically separated populations. Future studies should combine morphological identification with molecular authentication where feasible.

#### 4.8.3.2 Seasonal and Geographic Variation

Water temperature, light, nutrients, salinity, reproductive stage and other environmental conditions influence macroalgal chemistry. Therefore, a "standardized *Sargassum* extract" should specify:

- Species.
- Geographic origin.
- Collection date or season.
- Plant part where relevant.
- Pre-treatment.
- Extraction method.
- Solvent system.
- Yield.
- Molecular characteristics.
- Contaminant concentrations.

#### 4.8.3.3 Structural Heterogeneity

Fucoidan fractions with different molecular weights or sulfation patterns should not be assumed to have equivalent activity. Detailed chemical characterization must accompany biological experiments.

### 4.9 Contaminants

Potential contaminants include arsenic, heavy metals, excess salts, microbial contamination and persistent environmental pollutants. These concerns are especially important for drift or beach-cast biomass.

#### 4.9.1 Pharmacokinetics and Bioavailability

Many compounds show substantial activity when applied directly to cultured cells. Oral administration introduces additional barriers involving digestion, absorption, metabolism and excretion. The relationship between administered dose and biologically active concentration at a target tissue therefore requires substantially more investigation.

#### 4.9.2 Limited Clinical Evidence

Most therapeutic claims remain based on *in vitro* or animal evidence. The clinical literature is comparatively sparse. Human studies should employ standardized materials and report comprehensive safety outcomes.

#### 4.9.3 Regulatory Standardization

The intended product category determines the regulatory pathway. A crude food ingredient, standardized nutraceutical, medical biomaterial and pharmaceutical drug cannot be evaluated under identical criteria. Table 6 below presents knowledge gaps and future research priorities.

**Table 6: Major knowledge gaps and future research priorities**

| Knowledge gap | Why it matters | Recommended research priority |
|---|---|---|
| Limited species-specific standardization | "*Sargassum* extract" is chemically ambiguous | Establish authenticated species reference materials |
| Weak structure-function understanding | Bioactivity varies among polysaccharide fractions | Integrate NMR, molecular-weight, sulfation and biological analyses |
| Limited pharmacokinetic information | *In vitro* activity may not be bioavailable | Conduct absorption, metabolism and distribution studies |
| Insufficient chronic toxicity data | Therapeutic and feed applications may require repeated exposure | Perform standardized short- and long-term toxicology |
| Limited clinical trials | Preclinical evidence cannot establish human efficacy | Conduct well-powered controlled human studies |
| Contamination uncertainty | Beach-cast biomass may contain undesirable elements | Establish contaminant thresholds and batch testing |
| Seasonal chemical variation | Batch-to-batch inconsistency limits commercialization | Develop chemotype maps and harvest standards |

| | | |
|---|---|---|
| Incomplete aquaculture evidence | Results from one fish species may not generalize | Conduct multispecies feeding and challenge studies |
| Scale-up limitations | Laboratory extraction may not be commercially viable | Perform pilot-scale process and techno-economic assessments |
| Sustainability trade-offs | Intensive processing can increase environmental burdens | Apply life-cycle assessment to biorefinery systems |

### 4.9.4 Future Directions

Future *Sargassum* research should move from isolated demonstrations of bioactivity toward integrated translational pipelines. This would be useful because it would help translate promising *Sargassum* bioactivities into practical, evidence-based applications by linking compound discovery, mechanistic validation, safety assessment, standardization, scalability, and product development within a coordinated research framework. Such integrated pipelines could reduce duplication, identify the most therapeutically or industrially promising compounds more efficiently, and accelerate the transition from laboratory findings to clinically, nutraceutically, or commercially viable products.

The first priority is species-resolved chemistry. Large-scale chemical profiling should determine how metabolites vary among species, seasons and habitats. This would be useful because species-, season-, and habitat-resolved chemical profiling would identify the sources and conditions associated with the highest concentrations of bioactive metabolites, while reducing variability and supporting reproducibility. Such information would strengthen compound selection, improve standardization of *Sargassum*-derived products, and guide targeted harvesting and sustainable resource utilization.

The second priority is green extraction with biological validation. Extraction studies should report not only yield but also energy consumption, solvent requirements, molecular integrity and resulting biological activity.

The third priority is mechanism-based pharmacology. Rather than reporting that an extract is simply “antioxidant” or “anti-inflammatory,” future studies should identify molecular targets and establish concentration-response relationships.

The fourth priority is advanced formulation. Fucoidan and alginate offer opportunities for nanoparticles, hydrogels, scaffolds and controlled-release systems. These technologies may be particularly valuable where native compounds have poor stability or limited bioavailability.

The fifth priority is clinical translation. Promising fractions should progress through standardized chemistry, pharmacokinetics, toxicology, relevant animal models and carefully designed human studies.

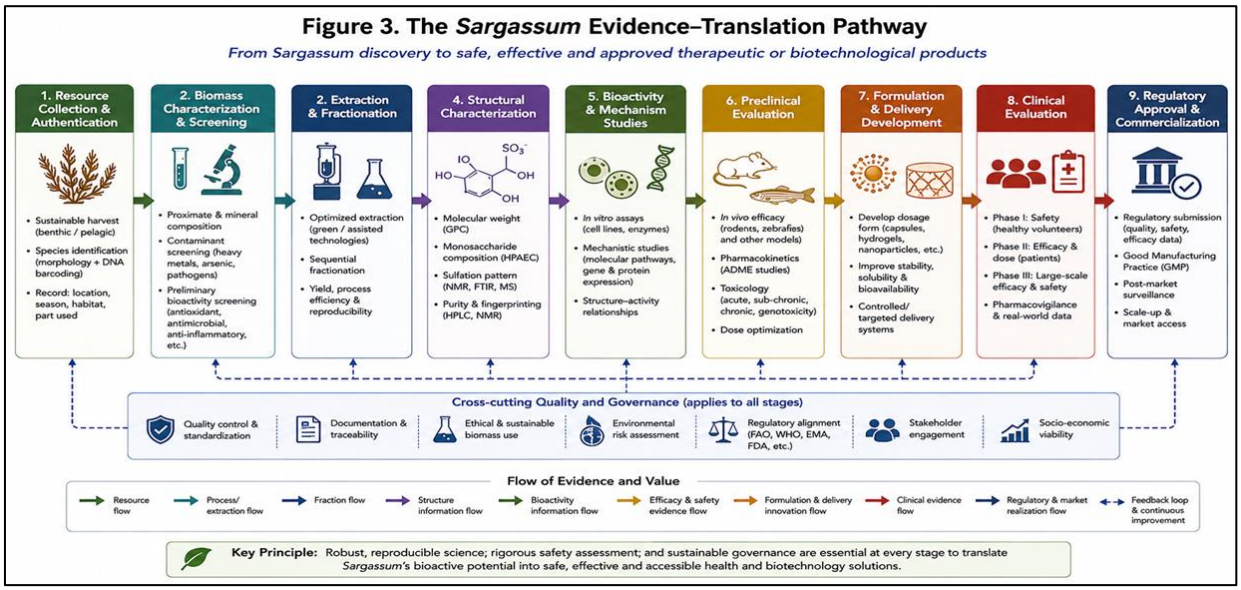


**Figure 3: Evidence-to-translation pathway for *Sargassum*-derived therapeutic development**

The central translational principle (Figure 3) is that demonstrated laboratory activity does not itself establish therapeutic efficacy. A successful *Sargassum*-derived therapeutic must satisfy multiple stages of evidence, including reproducible chemistry, biological mechanism, pharmacology, safety, formulation and clinical validation.

## 5 CONCLUSION

*Sargassum* species represent an important marine resource with substantial potential at the interface of biotechnology and therapeutics. Their importance derives from chemical diversity rather than from a single universally active compound. Fucoidan, alginate, laminaran, phlorotannins, carotenoids, terpenoids and other metabolites collectively provide opportunities for pharmaceutical discovery, nutraceutical development, biomaterials, wound management, drug delivery, functional aquaculture feeds, bioremediation and circular biorefineries.

Among the major therapeutic opportunities, antioxidant and anti-inflammatory effects are supported by a substantial preclinical literature, while antimicrobial, antiviral, immunomodulatory, metabolic and anticancer applications remain active areas of investigation. The strongest evidence should be interpreted according to the biological model used. Cell-culture results identify mechanisms and potential leads; animal studies provide additional biological relevance; controlled human trials remain essential for establishing clinical efficacy.

Alginate and fucoidan are particularly important components when considering biotechnology applications using *Sargassum*. Alginate provides a versatile, biocompatible platform for hydrogels, wound dressings and controlled delivery, whereas fucoidan combines intrinsic biological activity with potential as a component of advanced nanoparticles and other drug-delivery systems. *Sargassum* also has demonstrated relevance to aquaculture, where extracts or processed biomass may improve antioxidant defenses, immune responses and disease resistance.

The expansion of pelagic and beach-cast *Sargassum* biomass further strengthens the need for integrated biorefineries. However, the conversion of environmental biomass into therapeutic or food-grade products must be accompanied by rigorous contaminant screening. Pollutant accumulation may determine whether a particular biomass stream is suitable for pharmaceuticals, feed, bioremediation or only lower-value applications.

The future of *Sargassum* biotechnology depends on a transition from broad claims concerning “seaweed bioactivity” to precise, reproducible and species-specific science. The most promising pathway is an integrated model in which authenticated biomass is chemically characterized, extracted through sustainable technologies, fractionated into high-value products, evaluated through mechanistic and translational pharmacology and incorporated into a circular biorefinery that maximizes resource efficiency while protecting human and environmental health.

## STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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### *Disclosure of conflict of interest*

The authors certify that this submission is original work and is not under review at any other publication. The authors hereby declare that this manuscript does not have any conflict of interest.

### *Declaration of competing interest*

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### *Statement of informed consent*

The authors declare that informed consent was obtained from all individual participants included in the study. All work utilized in this study was fully cited and referenced so authors of prior researches are given their due credentials for their work.

### *Data Availability*

Data will be made available on request.

### *Credit Authorship Contribution Statement*

Lakhnarayan Kumar Bhagarathi- Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Aarif Baksh- Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Phillip N. B. Da Silva - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Vandevi Bhikam - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Yunita Arjune - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Ferial Pestano - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Sushmita Kalika-Singh - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing

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