recycling

MDPI

Review

Transforming Beach-Accumulated Seaweed into High-Value Bioactive Products: A Recycling Perspective

Dinusha Shiromala Dissanayake [1], Thilina U. Jayawardena [2,*] and Dineth P. Nagahawatta [2,*]

[1] Department of Marine Life Science, College of Ocean Science, Jeju National University, Jeju 63243, Republic of Korea; dinudissanayake95@stu.jejunu.ac.kr
[2] Department of Medicine, Faculty of Medicine and Dentistry, University of Alberta, Edmonton, AB T6G 2B7, Canada
* Correspondence: thilina@ualberta.ca (T.U.J.); dnagahaw@ualberta.ca (D.P.N.)

Abstract

Due to large-scale macroalgal blooms, nutrient enrichment, and changes in ocean circulation brought on by climate change, beach-accumulated seaweed (BAS) has quickly become a global environmental and waste-governance concern. Despite degradation and contamination during beach stranding, BAS retains valuable bioactive compounds, including sulfated polysaccharides, phlorotannins, pigments, proteins, peptides, and lipids, which exhibit anti-inflammatory, antioxidant, antimicrobial, antiviral, immunomodulatory, anticancer, and metabolic regulatory activities. This review critically evaluates BAS as a sustainable bioresource by integrating current knowledge on biomass composition, degradation-associated challenges, bioactive properties, valorization pathways, advanced extraction technologies, safety validation, regulatory considerations, and emerging commercialization opportunities. Attention is given to sustainable valorization pathways, ranging from composting and bioenergy production to the recovery of high-value bioactives through enzyme-assisted, green, and advanced extraction technologies. The review further discusses policy and regulatory gaps, contamination challenges, safety validation requirements, and life-cycle sustainability considerations that currently limit industrial adoption. Finally, emerging opportunities involving metabolomics, microbial bioprocessing, artificial intelligence, automation, and nanotechnology are explored as future directions for transforming BAS into a standardized and economically viable feedstock within the circular blue bioeconomy. Establishing harmonized regulatory frameworks and integrating BAS management with Sustainable Development Goals (SDGs) 12 and 14 will be critical for enabling sustainable resource recovery and long-term coastal resilience.

Keywords: beach-accumulated seaweed; biomass valorization; marine biomass recycling; marine bioactives; blue-bioeconomy; circular bioeconomy; algal biomass

Check for updates

Academic Editor: Michele John

Received: 14 May 2026
Revised: 24 June 2026
Accepted: 24 June 2026
Published: 26 June 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Beach-accumulated seaweed (BAS) has become a growing problem in many parts of the world, yet it remains an undervalued and under-addressed resource. Throughout the year, large quantities of macroalgae, such as *Sargassum*, *Ulva*, *Gracilaria*, and other mixed species, are washed onto shorelines [1]. Different environmental changes, including nutrient pollution, rising sea surface temperatures, and shifts in ocean currents, trigger these events. As a result, beach accumulation has gradually transformed from a seasonal inconvenience to a recurring global challenge for coastal communities [2].

Recent research findings and trends have drawn attention to the seaweed industry, and its rapid expansion has driven high demand for seaweed as a natural source of bioactive compounds, hydrocolloids, fertilizers, cosmetics, bioplastics, and nutraceutical ingredients. Across Asia, Europe, and America, seaweed is cultivated and carefully processed and transformed into valuable commercial products. However, the seaweed found on beaches, despite being fundamentally the same biological material, remains mostly ignored and is usually treated simply as waste [3,4].

The presence of decaying seaweed on beaches affects tourism, public health, and local fisheries. Strong odors caused by decomposing seaweed can release gases such as hydrogen sulfide, making beaches hostile and unsafe for residents and visitors. Also, it affects the local authorities and economies since the huge volume of stranded seaweed increases the cleanup costs [5]. Chemical characterization studies indicate that BAS retains substantial amounts of polysaccharides, polyphenols, pigments, lipids, proteins, and minerals despite varying degrees of degradation. However, much of the current understanding of the biological activities and industrial applications of these compounds originates from cultivated or freshly harvested seaweeds, highlighting the need for additional BAS-specific investigations [6]. Environmental stresses such as sunlight exposure, oxidation, high salinity resistance, and microbial interaction cause seaweed to possess entirely new or enhanced bioactivities compared to terrestrial plants [7]. This presents a unique opportunity to convert an environmental burden into a sustainable supply of raw materials.

Therefore, an urgent need to manage BAS arises, and a recycling-oriented approach should be introduced to address the issue instead of discarding or landfilling. With proper sorting, decontamination, and biorefinery processes, beach seaweed can be repurposed and integrated into the circular bioeconomy as valuable products. This shift helps not only to reduce environmental impact on the coastal ecosystem, but also to promote resource recovery, waste minimization, and sustainable development [8].

This review aims to critically evaluate BAS as a source of industrially relevant bioactive compounds by integrating current knowledge on biomass composition, degradation-associated challenges, valorization pathways, advanced extraction technologies, safety validation, and commercialization prospects within a circular bioeconomy framework. Unlike previous BAS reviews that primarily focused on biomass utilization opportunities, this review integrates chemical characterization, bioactivity, processing technologies, safety assessment, and commercialization challenges to provide a comprehensive roadmap for the valorization of high-value BAS.

2. Global Challenges of Beach-Accumulated Seaweed as an Emerging Waste Governance Problem

Beach-accumulated seaweed is no longer a local or seasonal inconvenience and is rapidly evolving into a complex waste governance issue due to several reasons. Global "green and golden tides" are affecting coastlines, degrading water quality, deterring tourists, and disrupting fisheries and aquaculture (Figure 1) [1]. The existing policies and waste management frameworks have not kept pace with the growing volume, variability, and unpredictability of this biomass [9]. To support this discussion, Table 1 synthesizes the main environmental, logistical, and regulatory challenges that must be addressed to enable sustainable recycling and bioactive recovery from beach-accumulated seaweed.

Table 1. Global challenges associated with BAS and their implications for waste management, recycling strategies, and bioactive recovery.

Challenge	Key Issue	Examples and Regional Context	Implications for Recycling/ Bioactive Recovery	References
Geographical Hotspots	Massive, recurrent accumulations of *Sargassum*, *Ulva*, and mixed macroalgae on global coastlines	Great Atlantic Sargassum Belt (Caribbean, Western Africa), Yellow Sea green tides (China, Korea), Northern Europe Ulva blooms	Seasonal unpredictability disrupts supply stability; batch variability affects extraction consistency	[10–12]
Species Variability	Mixed biomass containing brown, green, and red algae, often degraded	*Sargassum* spp., *Ulva* spp., *Gracilaria* spp., *Laminaria* spp. in unpredictable proportions	Difficulty in standardizing chemical composition and ensuring reproducible bioactivity profiles	[13,14]
Contaminant Load	Heavy metals, microplastics, sand, debris, marine animals, hydrocarbons, pathogens	Lead, cadmium, microplastics, *Vibrio* spp., and *E. coli* contamination in stranded seaweed	Requires extensive pre-cleaning → increases cost, reduces suitability for food/pharma applications	[15,16]
Degradation Processes	UV exposure, oxidation, enzymatic breakdown, and microbial decay during beach stranding	Loss of native metabolites, conversion to breakdown products, and release of H_2S gas	Chemical profile becomes unstable; some degradation products may have beneficial or harmful bioactivities	[17]
Waste Classification Ambiguity	Inconsistent legal status (waste, organic matter, invasive biomass) across countries	EU treats stranded seaweed as "beach waste," Caribbean countries classify Sargassum as "natural hazard."	Difficult to obtain permits for transportation and industrial processing due to regulatory uncertainty	[3,18]
Logistical Constraints	Large volumes, high moisture content, decomposition begins rapidly, and expensive removal	Manual/tractor removal is used in tourist beaches; rural areas lack the equipment	High operational costs: decomposition reduces usable yield and chemical stability	[19]
Economic Constraints	Low economic incentive to recycle; high processing costs; lack of dedicated supply chains	Tourism-dependent economies bear high cleaning costs without a revenue return	Recycling remains unattractive unless backed by policy support or subsidies	[19]
Regulatory Gaps	No standard quality criteria for beach biomass for industrial use	Absence of contamination limits, microbial guidelines, and hygiene protocols	Prevents certification for food/cosmetic-grade materials; limits international marketability	[20]
Lack of Infrastructure	Limited drying, storage, or processing facilities near affected beaches	Biomass is often left to rot; small local processors are overwhelmed	Limits rapid stabilization: transport to distant facilities is expensive	[14]
Social Acceptance Issues	Local communities often view biomass as a nuisance, not a resource	Negative tourism impact overshadows value-creation potential	Requires awareness campaigns and policy frameworks to normalize recycling	[21]

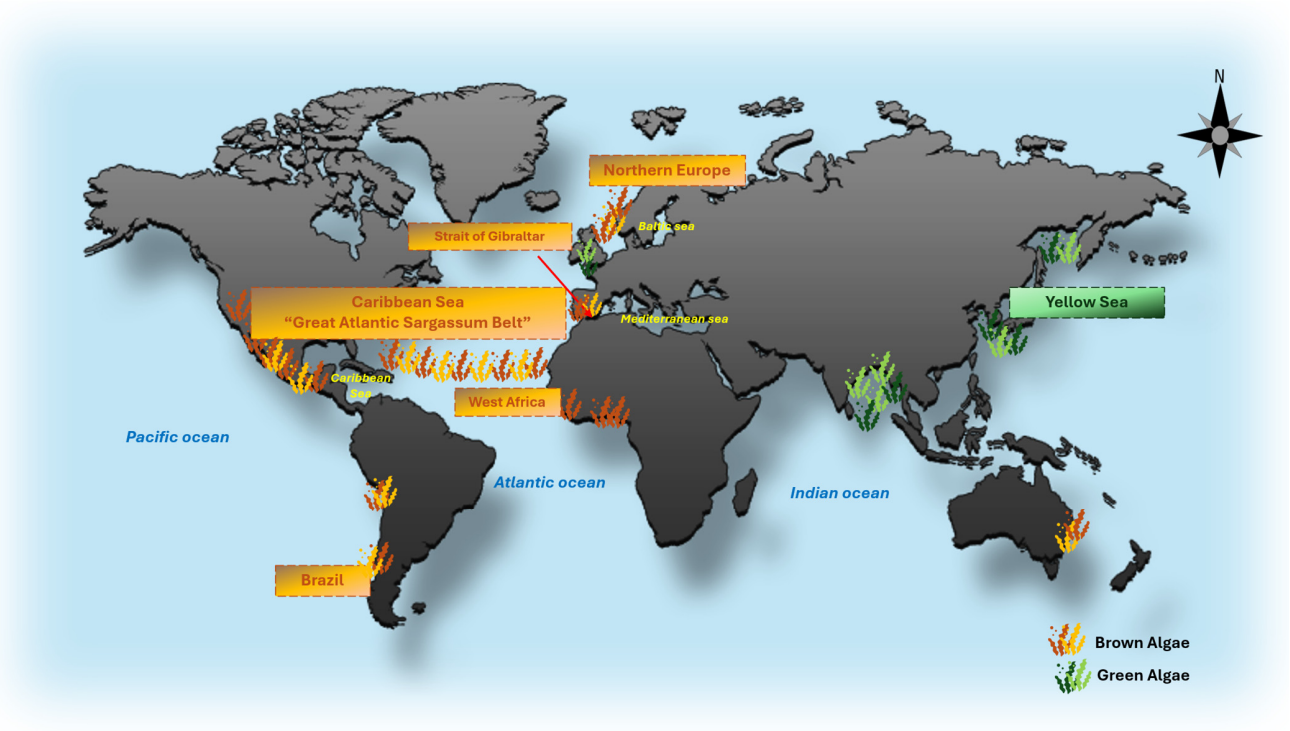


Figure 1. Global distribution of major beach-accumulated seaweed (BAS) hotspots associated with recurrent macroalgal blooms and coastal strandings. Major affected regions include the Great Atlantic Sargassum Belt (Caribbean and tropical Atlantic coasts), West Africa, Brazil, the Mediterranean region, Northern Europe, and the Yellow Sea. Orange symbols indicate predominant brown algal accumulations (ex. *Sargassum* spp.), while green symbols indicate predominant green algal accumulations (ex. *Ulva* spp.). The map highlights representative regions where large-scale seaweed strandings have generated environmental, socioeconomic, and management challenges [1,10,22].

3. Gaps in Worldwide Policies Regarding Seaweed Recycling

Global policies for seaweed recycling are fragmented and poorly aligned with the realities of large-scale beach strandings. Within the European Union (EU), reuse is constrained due to contamination thresholds and product-safety regulations, despite broader commitments made under the Circular Economy Action Plan and EU Bioeconomy Strategy [23]. Pilot initiatives in France and Portugal demonstrate the technical feasibility of converting stranded *Ulva* into compost, biogas, and agricultural products, but regulatory conditions remain restrictive [24].

In the Caribbean and West Africa, policy focuses almost entirely on emergency *Sargassum* removal to protect tourism and public health, with minimal long-term guidance for recycling pathways [25]. East Asian nations such as China, Korea, and Japan have advanced seaweed aquaculture regulations, yet stranded biomass is generally treated as a separate, unmanaged category [26]. Global initiatives, including the United Nations Environment Programme (UNEP)'s *Sargassum* management programs, signal growing interest in coordinated responses, but the absence of standardized contamination protocols, resource classifications, and operational guidelines still limits the scalability of recycling efforts [27].

3.1. Alignment with SDG 12 and SDG 14

Recycling BAS aligns strongly with both SDG 12 (Responsible Consumption and Production) and SDG 14 (Life Below Water) [28,29]. Transforming stranded biomass into fertilizers, biogas, bioplastics, or biostimulants supports SDG 12 by reducing waste, improving material efficiency, and diverting organic matter from landfills. At the same

time, removal of decaying biomass mitigates hydrogen sulfide emissions, eutrophication, and local pollution, contributing to SDG 14's goals of protecting marine ecosystems.

However, trade-offs must be acknowledged. Large-scale removal may disturb beach ecosystems and conflict with conservation objectives or local livelihoods, highlighting potential tensions between SDG 14 and socio-economic equity. Moreover, SDG monitoring suffers from ambiguous indicators, making it difficult to assess whether interventions genuinely reduce pollution or simply shift burdens downstream. Effective integration with the SDGs, therefore, requires governance frameworks that balance ecological protection, social justice, and long-term monitoring [30].

3.2. Blue Bioeconomy and High-Value Marine Bioactives

The blue bioeconomy emphasizes the sustainable use of aquatic biomass for high-value products such as nutraceuticals, pharmaceuticals, biopolymers, and cosmeceuticals [31]. While EU-level strategic frameworks (e.g., Sustainable Blue Economy Strategy, Green Deal, Circular Economy Action Plan) [32,33] recognize the value of marine resources, they do not provide clear pathways for integrating beach-cast seaweed into regulated markets.

Environmental directives such as the Marine Strategy Framework Directive regulate coastal ecosystem protection, but do not address how to balance conservation with sustainable removal for recycling [34]. Thus, beach-cast biomass remains trapped in a policy gap, recognized as a potential resource but treated operationally as waste.

3.3. Policy Gaps Relevant to Food-, Cosmetic-, and Pharma-Grade Applications

BAS faces substantial regulatory barriers in high-value industries due to unresolved issues in contamination control, standardization, and product classification. Current regulations were designed for clean, cultivated seaweed and do not account for the heavy metals, microplastics, pathogens, and debris commonly found in stranded biomass. No harmonized guidelines exist for monitoring contaminants, setting acceptable limits, or defining pre-processing requirements [35].

High-value applications require strict traceability and compositional consistency, and this creates BAS challenges for meeting Novel Food authorizations, cosmetic ingredient standards, and pharmaceutical-grade specifications [36]. Regulatory ambiguity, particularly around intermediate categories like cosmeceuticals, further delays innovation and commercialization. Overall, the primary obstacles are not explicit prohibitions but the absence of clear legal definitions, standardized contamination thresholds, and dedicated regulatory routes for transforming stranded seaweed into safe, marketable products [37].

4. Chemical and Bioactive Potential of BAS

Despite being widely considered an environmental nuisance, BAS consists of a broad spectrum of bioactive compounds with significant industrial relevance. Its highly advanced biochemical profile, ranging from marine polysaccharides and antioxidant polyphenolics to secondary metabolites with a wide range of bioactivities, highlights considerable opportunities for high-value product development if safety and variability challenges can be addressed [38]. Table 2 summarizes the approximate composition of BAS.

Table 2. Approximate macro-composition of beach-accumulated seaweed.

Component	Typical Range in Dry Weight (%)	Notes	References
Polysaccharides	30–80	Highest in brown algae; includes fucoidan, alginate, cellulose, mannitol,	[4,39]
Protein	5–28	Species dependent; some red and green algal species reach >20%	[4]

Table 2. *Cont.*

Component	Typical Range in Dry Weight (%)	Notes	References
Lipids	0.27–4.3	High in phytosterols; Omega-3 and 6 balanced	[40]
Ash (total mineral fraction)	6.5–59	High amounts of macro elements, including Na, K, Ca, Mg, and P, trace minerals, including heavy metals (0.1–100 mg/kg)	[41,42]

4.1. Chemical Profiles: Polysaccharides, Phlorotannins, Pigments, Proteins, Lipids

This section provides a deep insight into the major chemical compounds present in BAS that can be used to develop high-value bioactive products. It should be noted that the most detailed compositional and bioactivity studies have been conducted using cultivated or freshly harvested seaweed. Although available evidence suggests that BAS retains many of the same compound classes, environmental exposure, microbial degradation, and contamination may alter both composition and functionality. Consequently, findings from cultivated seaweed should be interpreted with caution when extrapolated to BAS.

4.1.1. Polysaccharides

The most dominant chemical fraction in many macroalgal groups is polysaccharides. Alginates, fucoidans, and laminarin are found in brown seaweeds; agar, carrageenan, and porphyran are found in red seaweeds; and ulvan and associated sulfated heteropolysaccharides are found in green seaweeds [43]. Viscosity, gelation, bioactivity, and industrial usability are all impacted by the structural complexity of these polymers, which include different sulfation patterns, monosaccharide ratios, and glycosidic connections [44]. Although partial degradation and salt infiltration can alter their molecular weight distribution and functional properties, polysaccharides nevertheless have considerable gelling, stabilizing, and immunomodulatory potential even in beach-cast biomass [45].

4.1.2. Phlorotannins

Phlorotannins are a significant and unique class of polyphenols synthesized by many seaweeds, especially brown seaweeds, and play a central role in stress tolerance. Their presence in beach-accumulated biomass is particularly noteworthy because these compounds confer strong antioxidant, anti-inflammatory, antimicrobial, and anti-UV properties. Structurally based on phloroglucinol units, phlorotannins vary from small oligomers to large polymers, providing a wide range of biological activities [46]. Studies have reported that in Australian beach-cast species, in vitro digestion released phloroglucinol, gallic acid, protocatechuic acid, and other phenolic compounds [47]. Also, tannins and flavonoids were particularly notable in some brown seaweed species [48]. However, environmental degradation and microbial action can reduce their stability, leading to oxidative polymerization or leaching. Despite this, significant phlorotannin content can still be recovered from many beach-cast brown species, offering a valuable resource for cosmetic and nutraceutical applications.

4.1.3. Pigments

Many macroalgal pigments have both functional and sensory properties, and they remain chemically stable even after prolonged exposure to sunlight. Brown algae contain fucoxanthin and chlorophyll c, red algae contain phycoerythrin, phycocyanin, and carotenoids, and green algae contain lutein and chlorophylls a and b [49]. These pigments are potent photo-protective and antioxidant agents; fucoxanthin has anti-inflammatory, anti-obesity, and anticancer qualities. Oxidative stress and UV exposure can reduce pigment concentrations in beach-cast seaweed, but quantifiable amounts usually persist, and degraded derivatives may still have biological activity [50].

4.1.4. Proteins

Seaweed proteins constitute a smaller but significant fraction and include enzymes, structural proteins, lectins, peptides, and mycosporine-like amino acids (MAAs). These compounds contribute to antioxidant, antimicrobial, and photoprotective functions [51]. In fresh seaweed, protein content can range from 5 to 47% of dry weight, depending on species. Nonetheless, bioactive peptides can still be generated during natural breakdown, sometimes enhancing the functional potential of the biomass when processed appropriately [4].

4.1.5. Lipids

Seaweeds' lipid fraction is remarkably rich in bioactive components, such as polyunsaturated fatty acids (PUFAs), glycolipids, phospholipids, and sterols, despite their generally low total lipid content (1–10% of dry weight) [40]. Green algae supply different amounts of omega-3 and omega-6 fatty acids, red algae contain eicosapentaenoic acid (EPA) and other sulfolipids, and brown algae contain fucoxanthin derivatives [52]. In beach-cast conditions, lipids are vulnerable to oxidation, but substantial fractions can still be recovered, especially in species with thicker thalli that slow degradation. These lipids have chemopreventive, antiviral, antimicrobial, and anti-inflammatory properties [40].

4.2. Core Bioactivities Underpinning the High-Value Potential of BAS

BAS has a wide range of bioactivities and strong potential for high-value industrial applications (Figure 2). By inhibiting key mediators like TNF-α, IL-1β, COX-2, and NF-κB, BAS exhibits strong anti-inflammatory activity, and phlorotannins control MAPK signaling [53]. Through radical scavenging, metal chelation, and UV-protective carotenoids like fucoxanthin, BAS also maintains a potent antioxidant capacity; degradation-derived oligomers frequently increase antioxidant efficiency [54]. Phlorotannin-induced membrane disruption, peptide-mediated pore formation, and sulfated polysaccharide interactions that prevent viral attachment and replication are the sources of its antimicrobial and antiviral characteristics [55]. Smaller fragments generated by environmental exposure improve receptor accessibility, and fucoidan and ulvan-associated activation of macrophages, NK cells, and T-cell pathways mediates immunomodulatory effects [56]. Apoptosis induction, cell-cycle arrest, and angiogenesis inhibition through caspase activation, Bax/Bcl-2 modulation, and suppression of PI3K/Akt and VEGF pathways are all thought to have anti-cancer potential [57]. Sulfated polysaccharides enhance glucose metabolism and gut microbiota balance, while fucoxanthin stimulates thermogenesis and AMPK activation. BAS also plays a role in metabolic regulation [58]. Table 3 summarizes the major bioactivities of BAS, their industrial significance, and challenges related to degradation. While many of the reported bioactivities have been extensively demonstrated in cultivated seaweed, relatively few studies have directly evaluated these activities in BAS-derived extracts. Therefore, the biological potential described here should be considered indicative rather than universally confirmed for all BAS materials.

Table 3. Functional properties and potential industrial applications, highlighting challenges posed by degradation and contamination in stranded biomass.

Bioactive Class	Bioactivities/ Functional Properties	Potential Industrial Applications	Key Challenges (Beach Biomass Specific)	References
Sulfated Polysaccharides	Anti-inflammatory, antiviral, anticoagulant, immunomodulatory, prebiotic	Nutraceuticals, pharmaceuticals, wound healing gels, biomaterials	Sand/salt contamination; degradation decreases MW and bioactivity; heavy metals must be removed	[59–61]
Phlorotannins	Antioxidant, anti-aging, anti-diabetic, UV-protective, anti-bacterial	Cosmetics, sun-care formulations, anti-aging products	UV-induced oxidation reduces activity; extraction requires solvent clarification due to debris	[62,63]

Table 3. *Cont.*

Bioactive Class	Bioactivities/ Functional Properties	Potential Industrial Applications	Key Challenges (Beach Biomass Specific)	References
Pigments	Anti-obesity, anti-cancer, antioxidant, anti-inflammatory	Functional foods, nutraceuticals, and natural colorants	Light degradation reduces pigment stability; microbial contamination affects purity	[64]
Proteins & Peptides	ACE-inhibitory (antihypertensive), antioxidant, anti-inflammatory	Functional foods, peptide supplements, and biomedical applications	Proteolysis during decomposition alters peptide profiles; needs rapid stabilization	[65]
Lipids & Sterols	Anti-inflammatory, cholesterol-lowering, membrane-stabilizing	Nutraceutical oils, cosmetic emollients	Oxidation occurs quickly on beaches; lipid purity is compromised by debris	[66]
Fibers	Prebiotic and gut health benefits	Animal feed, fertilizers, food ingredient blends	Sand and microplastics must be separated; needs washing and decontamination	[67]
Phenolic Compounds	Antioxidant, antimicrobial, anti-inflammatory	Cosmetics, food preservatives, and antimicrobial coatings	Environmental exposure modifies phenolic concentration; must remove co-contaminants	[68]
Terpenoids and other secondary metabolites such as Sterols, halogenated compounds, and Diterpenes	Antibacterial, antifungal, cytotoxic, signaling molecules	Drug discovery, pest control, antifouling coatings	Trace amounts require sophisticated extraction; high debris load complicates purification	[69,70]
Microbial Co-metabolites	Possible novel antibiotics, anti-inflammatory agents	Bioprospecting for pharmaceuticals	Hard to isolate; microbial safety concerns; requires careful separation	[71]
Mineral Components	Thyroid-supporting mineral supplements and plant growth enhancers	Nutraceuticals, dietary mineral supplements, Agriculture, fertilizers	Excess iodine or heavy metals can pose toxicity risks; strict limits are required	[16,72]

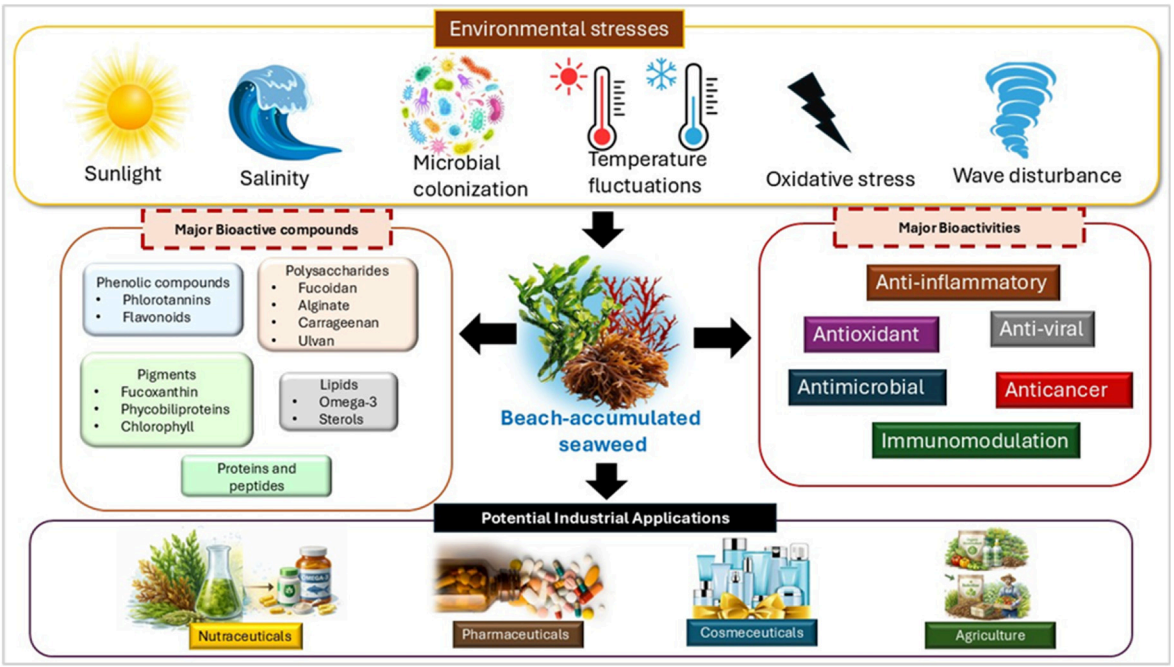


Figure 2. Beach-accumulated seaweed: environmental drivers, biological compositions, bioactivities, and potential industrial applications.

4.3. Commercial Significance and Valorization Pathways of BAS

BAS presents both challenges and opportunities for recycling and circular bioeconomy applications and remains a significant organic resource that can be directed into diverse valorization pathways. These range from low-value, high-volume processes such

as composting and biogas production to more specialized extraction of high-value bioactive compounds, provided that appropriate pretreatment approaches are applied [73]. The following subsections outline the most promising technological and biorefinery routes for managing stranded seaweed in a sustainable and economically feasible manner.

4.3.1. Low-Value/High-Volume Valorization Pathways

Low-value, high-volume pathways are particularly suitable for BAS because they can tolerate variability in species composition, moisture content, and degradation stage. Composting is one of the most widely tested applications, as seaweed can supply essential minerals and improve soil structure when mixed with carbon-rich organic substrates [14]. However, successful composting requires reducing salt levels through washing or rain-leaching and screening to remove sand and debris. When properly managed, seaweed compost enhances soil fertility and can replace synthetic fertilizers in agriculture, landscaping, and coastal dune restoration programs [74].

Anaerobic digestion (biogas production) is another scalable route, as macroalgae are rich in carbohydrates that are readily converted into methane. Yet, high salinity, sulfur content, and microbial contamination can inhibit digestion efficiency, requiring dilution or co-digestion with other organic wastes [18]. Biogas output from stranded *Sargassum* and *Ulva* has been demonstrated in pilot trials in the Caribbean and Europe, but challenges remain in continuously supplying biomass of consistent quality [75]. Similarly, seaweed can be processed into soil conditioners or biochar through pyrolysis, offering carbon sequestration benefits and improving nutrient retention when applied to agricultural lands [76].

Animal feed represents a potential, but more restricted pathway, as contamination with heavy metals and pathogens may require rigorous screening [77]. While cultivated seaweed is used widely in livestock and aquaculture diets, stranded biomass requires decontamination steps, species sorting, and chemical testing before approval. In regions with relatively clean accumulations, such as parts of Europe, controlled incorporation of *Ulva* into animal feed has shown promise [78]. Overall, these low-value pathways support large-scale biomass utilization but require infrastructure for cleaning, pretreatment, and safe handling.

4.3.2. High-Value/Low-Volume Valorization Pathways

High-value pathways focus on extracting specific bioactive compounds, biopolymers, pigments, and other compounds with pharmaceutical, nutraceutical, cosmetic, or biomaterial applications. BAS contains sulfated polysaccharides (such as fucoidan, alginate, carrageenan, and ulvan), phlorotannins, pigments like fucoxanthin, proteins and peptides, and lipid fractions with bioactive properties [38]. However, the suitability of stranded biomass for high-value extraction depends on its chemical integrity, which can be compromised by sun exposure, oxidation, microbial degradation, and contamination.

Pharmaceutical and Biomedical Industry

Pharmaceutical applications require the highest degree of purity, bioactivity validation, and chemical consistency, which poses significant challenges for beach biomass. However, with advanced purification, beach-derived compounds can be positioned as therapeutic candidates or biomedical material components [79].

The antimicrobial and antiviral properties of phlorotannins and sulfated polysaccharides enable applications in natural preservation, active packaging films, and biomedical coatings, providing alternatives to synthetic preservatives and antimicrobial agents [80]. In drug delivery systems, alginate is widely used to form ionically cross-linked hydrogels that enable sustained and controlled release of encapsulated drugs, and also aid high absorbance, biocompatibility, and provide a moist healing environment [81]. Fucoidan can be

formulated into nanoparticles that selectively target sites of inflammation or tumor tissues through receptor-mediated interactions [82]. Also, fucoidan-containing formulations have been investigated for anti-inflammatory therapies, cancer adjunct treatments, and targeted drug-delivery systems owing to their ability to interact with selectins and growth factors. These polymers can also be blended into composite scaffolds that support tissue engineering by providing mechanical stability and biomimetic environments for cell growth [83]. Bioactive peptides and low-molecular-weight polysaccharides formed during natural environmental degradation enhance potential use in wound-healing gels, hydrogels, and tissue regeneration scaffolds due to their biocompatibility and immunomodulatory effects [84].

Functional Food, Nutraceutical, and Cosmeceutical Industry

In the nutraceutical industry, market applications include dietary fibers and prebiotic supplements in the form of capsules, powders, or beverages, immune-boosting nutraceutical blends targeting macrophage activation or antiviral responses, metabolic health formulations using fucoxanthin and low molecular weight fucoidan, and functional drinks with mineral-rich extracts [85]. Fucoxanthin-rich extracts are increasingly marketed in weight-management and metabolic-health supplements because of their effects on lipid metabolism and thermogenesis. Fucovital® and ThinOgen® are commercially available supplements manufactured using fucoxanthin that help in weight loss, brain, eye, liver, and joint health [86]. Fucoidan-based products are widely sold as immune-support nutraceuticals in capsule, tablet, and beverage formulations [87]. Similarly, phlorotannin-rich extracts have attracted attention as natural antioxidant ingredients in functional food and dietary supplements. These examples demonstrate that BAS-derived compounds possess direct commercial relevance beyond their biological activities.

Cosmeceutical markets also benefit from seaweed-derived pigments and polysaccharides, which offer anti-aging, photoprotective, anti-inflammatory, and skin-repair functions. Their natural origin aligns well with consumer demand for clean, sustainable ingredients. Potential cosmetic product categories are serums and essences enriched with low molecular weight fucoidan, anti-aging creams with phlorotannin-rich extracts, sunscreen boosters incorporating fucoxanthin, anti-acne gels using antimicrobial alginate oligosaccharides, and haircare formulations for strengthening and scalp health [88].

Overall, compared with bulk applications such as composting or biorefinery production, the extraction of bioactive compounds offers substantially higher economic returns per unit biomass, making pharmaceutical, nutraceutical, and cosmeceutical sectors particularly attractive targets for BAS valorization.

Despite their significant commercial potential, high-value applications face substantial barriers, including variability in biomass composition, contamination by heavy metals and microplastics, regulatory approval requirements, and the high costs associated with purification and quality assurance. These challenges may limit large-scale commercialization unless standardized processing frameworks are established [89]. Figure 3 summarizes the valorization pathways of BAS with their potential industrial applications.

4.4. Pretreatment and Enzyme-Assisted Technologies to Harness Bioactives from BAS

Effective pretreatment is essential for stabilizing BAS and preparing it for either low-value or high-value valorization. Key pretreatment steps include manual or mechanical removal of sand, plastics, and debris; washing to reduce salt and microbial load; and drying or ensiling to halt enzymatic degradation [18]. Technologies such as air classification, sieving, flotation, and density separation can significantly improve biomass quality by removing sediments and microplastics. Dewatering through mechanical pressing or solar drying reduces transport costs and increases storage stability [90].

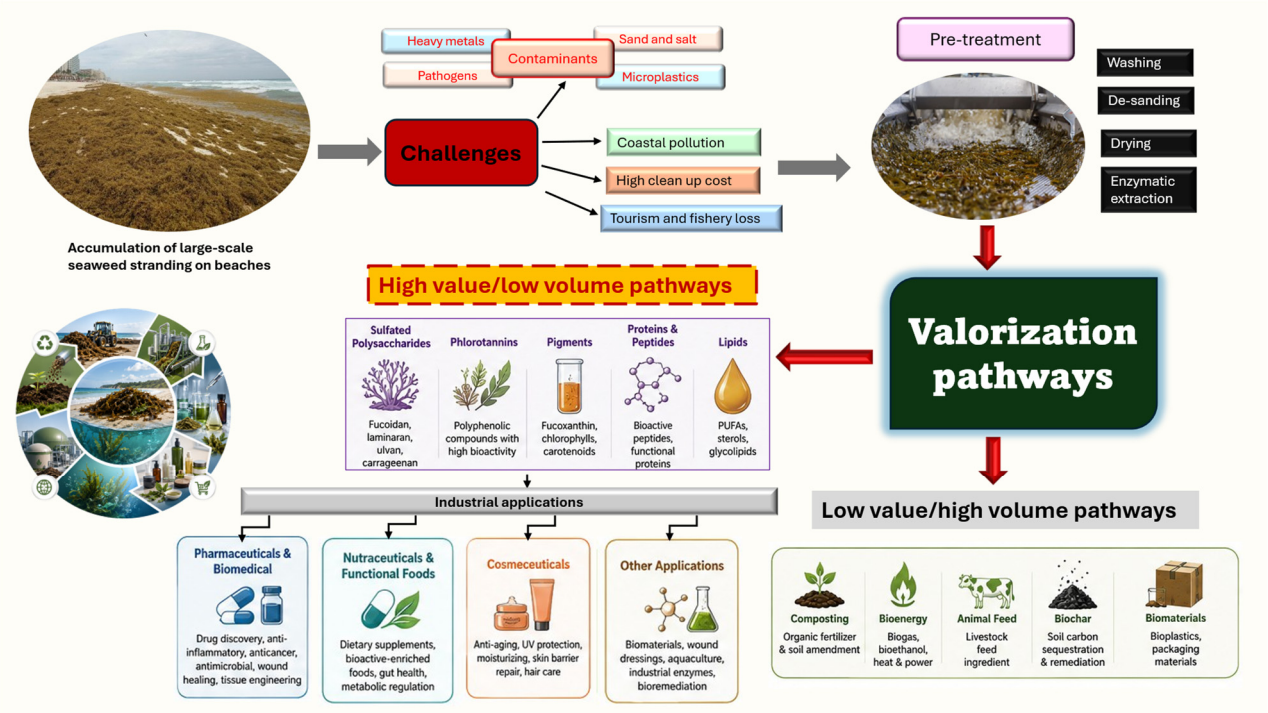


Figure 3. Valorization pathways of Beach-accumulated seaweed (BAS).

Enzyme-assisted extraction technologies offer a more refined approach for recovering polysaccharides, proteins, and phenolic compounds. Enzymes such as cellulases, proteases, and carbohydrases can selectively break down cell walls and release target molecules, improving extraction yields and reducing the need for harsh chemicals [91]. This is especially important for degraded stranded biomass, where enzymes can help recover partially altered biomolecules. However, implementing pretreatment technologies requires investment in coastal processing infrastructure, which is often lacking in regions most affected by seaweed influxes. Developing decentralized or mobile processing units could help overcome logistical challenges and enable rapid stabilization at the collection site [92].

Although enzyme-assisted extraction offers improved selectivity and environmental benefits, industrial implementation remains challenging due to enzyme costs, substrate-specific optimization requirements, and reduced efficiency when processing heterogeneous or highly degraded beach-cast biomass. Furthermore, large-scale pretreatment infrastructure is often unavailable in coastal regions most affected by BAS accumulation [93].

4.5. Advanced Extraction and Fractionation Technologies for Bioactive Recovery of BAS

Well-adapted extraction strategies are required for the efficient recovery of high-value bioactives from BAS, considering their chemical complexity and environmental variability. Modern extraction approaches primarily focus on preserving sensitive biomolecules, enhancing yield, and minimizing contaminants such as salt, sand, microbial metabolites, and heavy metals [94]. Tailored and green extraction techniques support the transformation of BAS biomass into standardized, industry-ready ingredients for nutraceuticals, pharmaceuticals, cosmetics, and agriculture.

While advanced extraction technologies improve recovery efficiency and product quality, their widespread adoption may be constrained by high capital investment, energy requirements, specialized equipment, and technical expertise. For example, supercritical CO_2 extraction and membrane-based fractionation often require substantial operational costs that may be difficult to justify for low-value or highly variable feedstocks such as BAS.

Moreover, differences in species composition and degradation status can affect extraction reproducibility and product standardization [95].

4.5.1. Tailored Extraction Based on Compound Classes

Depending on their chemical nature and structural sensitivity, different classes of bioactives in BAS require customized extraction strategies. To selectively isolate fractions based on charge density and molecular weight, sulfated polysaccharides like fucoidan, carrageenan, and ulvan are usually extracted using hot-water extraction, graded ethanol precipitation, ion-exchange chromatography, or membrane ultrafiltration [96]. Additionally, these procedures eliminate salt and inorganic contaminants derived from sand that are frequently present in beach-cast samples. Reported fucoidan extraction yields vary considerably depending on species and extraction conditions, ranging from approximately 6–15% in many *Sargassum* species to over 20% in optimized extraction systems, while some *Fucaceae* species have yielded up to 48–83% crude polysaccharide fractions. Such variability highlights the importance of extraction optimization and biomass selection [97].

Aqueous ethanol, methanol, or acetone are the best solvents for recovering phenolic compounds, particularly phlorotannins, with careful pH control to avoid polymerization. Phlorotannin-rich fractions can be further purified using solid-phase extraction (SPE) and preparative HPLC, particularly when focusing on particular oligomers with more potent anti-inflammatory or antioxidant properties [98].

Fucoxanthin, chlorophylls, and phycobiliproteins are examples of pigments that must be extracted under low light and oxygen conditions using either buffered aqueous systems (for phycobiliproteins) or cold organic solvents (for carotenoids). Accelerated solvent extraction (ASE), supercritical CO_2 (for higher purity), or mild enzymatic treatment to prevent oxidation are commonly used to isolate lipids and PUFAs. Every compound class is recovered with the highest level of structural integrity and biological activity, thanks to tailored extraction [99]. Pressurized liquid extraction and related green technologies typically achieve crude fucoidan yields of approximately 13–24%, often exceeding those obtained by conventional extraction methods.

4.5.2. Green Extraction Technologies for Sensitive Biomolecules

To recover bioactives from BAS without sacrificing bioactivity, sustainability, or safety, green extraction techniques have become crucial. Supercritical CO_2 extraction (SC-CO_2) provides solvent-free recovery of sterols, lipids, and pigments with minimal oxidation and high selectivity. Additionally, SC-CO_2 can extract phenolics more effectively when combined with co-solvents like ethanol [97].

For thermolabile compounds, ultrasound-assisted extraction (UAE) improves recovery of polysaccharides, phenolics, and pigments at lower temperatures and shorter extraction times by enhancing cell-wall disruption [100]. Quantitative comparisons have demonstrated that UAE can increase extraction yields by approximately 20–50% while reducing solvent consumption by up to 50% compared with conventional extraction approaches. In brown seaweeds, extraction yields of 20.4–36.9% have been reported using UAE, compared with 10.5–19.3% using conventional solvent extraction [101]. By speeding up the penetration of water into seaweed matrices, microwave-assisted extraction (MAE) increases the efficiency of protein and polysaccharide extraction while using less solvent [102]. Similarly, microwave-assisted and combined ultrasound–microwave extraction systems have shown improvements in polysaccharide and phenolic recovery, with reported crude polysaccharide yields frequently exceeding 15–20% depending on species and processing conditions [97]. Pressurized liquid extraction (PLE) and natural deep eutectic solvents (NADES) provide additional green options for compounds sensitive to oxidation or thermal

breakdown. In addition to optimizing the recovery of delicate biomolecules from beach-cast seaweed, these technologies satisfy environmental and regulatory standards for sustainable, clean-label production [103].

4.5.3. Safety and Validation

A comprehensive safety assessment framework is essential before BAS can be incorporated into food, cosmetic, or pharmaceutical products due to the high risk of environmental contamination and degradation. The first layer of evaluation focuses on contaminant testing, requiring systematic analysis of heavy metals such as arsenic, cadmium, lead, and mercury, which can accumulate in stranded biomass, as well as quantification of microplastics, sand particulates, pathogenic microbes, and organic pollutants, including hydrocarbons and pesticide residues [104]. For example, analyses of commercially available seaweed have reported average concentrations of approximately 17.4 mg/kg dry weight (DW) for total arsenic, 0.7 mg/kg DW for lead, 0.5 mg/kg DW for cadmium, and 0.01 mg/kg DW for mercury, although substantial variation occurs among species and geographic regions. These findings emphasize the necessity of contaminant monitoring before BAS can be utilized in food, cosmetic, or pharmaceutical applications [105]. Following contaminant screening, stability testing ensures that recovered bioactives maintain their integrity throughout processing and storage by assessing oxidative stability, molecular weight changes in polysaccharides, pigment and phenolic degradation, shelf-life under heat, light, and humidity fluctuations, and potential microbial regrowth after extraction [106]. Finally, toxicological evaluation provides biological safety validation through in vitro cytotoxicity assays using relevant cell lines such as RAW macrophages, HaCaT keratinocytes, or fibroblasts; hemocompatibility tests for materials intended for pharmaceutical or biomedical applications; and simulated gastrointestinal digestion models to confirm the safety and bioaccessibility of compounds destined for nutraceutical use [107]. Together, these assessments form a rigorous safety pipeline that ensures BAS is transformed into clean, stable, and biologically safe raw material suitable for high-value industrial applications. An overview of the major contamination risks associated with BAS, along with their regulatory and industrial implications, is presented in Table 4.

Table 4. Major contamination risks associated with BAS and their regulatory and industrial implications.

Contaminant Category	Examples	Regulatory Concerns	Practical Implications for BAS Valorization	References
Heavy metals	As, Cd, Pb, Hg	Food and feed products must comply with national limits (EU, FDA, Korean MFDS)	Requires routine contaminant screening before nutraceutical or food applications	[16,105]
Microplastics	PE, PP, PET fragments and fibers	No harmonized regulatory limits currently exist	May require washing, flotation, and density separation pretreatments	[20,90]
Pathogens	*Vibrio* spp., *Salmonella* spp., *E. coli*	Microbiological standards apply for food, feed, and cosmetic ingredients	Drying, sanitization, and extraction steps are necessary	[7,17]
Organic pollutants	Hydrocarbons, pesticides, PAHs	Subject to food safety and environmental regulations	Limits suitability for direct food or pharmaceutical use	[17,20]
Degradation products	Oxidized lipids, degraded pigments, and low-molecular-weight compounds	No specific thresholds, but they affect product quality and stability	Can reduce bioactivity and extraction yields	[38]

When translating BAS-derived bioactives, proper validation and regulation must be established to make them legally compliant and market-ready products. For functional foods

and nutraceuticals, manufacturers must meet Codex Alimentarius and FDA dietary ingredient standards, including verification of identity, purity, and safety, followed by human clinical studies, typically Phase 0–I trials, to substantiate any claimed health benefits [108]. In the cosmetic and cosmeceutical industry, regulatory approval requires compliance with frameworks such as the EU Cosmetics Regulation or the Korean KFDA guidelines, which mandate detailed safety assessments, toxicological dossiers, and dermatological patch testing to ensure formulations do not cause irritation or sensitization [109]. Pharmaceutical applications demand the most stringent pathway, requiring GMP-certified manufacturing, full pharmacokinetic and biodistribution studies, and comprehensive preclinical toxicity testing before progressing through Phase I–III clinical trials to confirm safety, efficacy, and therapeutic performance [110]. Together, these tiered regulatory routes ensure that bioactive ingredients derived from BAS are validated through rigorous scientific and safety standards tailored to each industry's requirements.

5. Environmental and Economic Sustainability: A Life-Cycle Assessment (LCA) Perspective

The environmental performance and economic viability of BAS valorization throughout the biomass' whole life cycle are just as important to its sustainability as its technological viability. A methodical assessment of energy inputs, emissions, avoided environmental burdens, and resource efficiency from collection to final product utilization is made possible by applying a life-cycle assessment (LCA) perspective [111]. Techno-economic analysis (TEA) simultaneously determines potential revenue streams, economic bottlenecks, and the primary cost drivers [112]. Together, these evaluations establish whether BAS-based biorefineries can function competitively, sustainably, and at a scale appropriate for coastal areas that frequently experience significant influxes of seaweed [113].

5.1. Environmental Impact Assessment

Compared to conventional disposal techniques like landfilling or open dumping, BAS offers several clear environmental benefits. The most energy-intensive processes, according to LCA analysis, are collection, transportation, and drying, particularly when long-distance hauling or mechanical dryers are needed [111]. Extraction processes, particularly those involving solvent heating, pressurization, or multiple purification stages, also contribute a measurable carbon footprint [114]. However, significant environmental advantages specific to BAS recycling usually outweigh these effects. Significant methane and hydrogen sulfide emissions are prevented by removing stranded biomass before anaerobic decay, which also improves coastal air quality [115]. Additionally, vital plant nutrients like nitrogen, potassium, calcium, and trace minerals are returned to the soil when BAS is converted into compost or digestate, lowering the need for synthetic fertilizers and promoting nutrient circularity [116]. By substituting natural materials for petrochemical-derived antioxidants, preservatives, thickeners, and biostimulants, biorefineries that generate bioactives can also reduce their environmental impact [117]. Overall, LCA data show that when collection, transportation, and drying are optimized for low energy consumption, BAS valorization can result in net environmental benefits [115].

5.2. Economic Feasibility (Techno-Economic Drivers)

Whether BAS valorization can move from pilot to commercial scale depends in large part on its economic viability. Most of the costs are associated with collection and transportation, which call for a large amount of labor, fuel, and equipment, especially when the biomass is wet and spread out along the shoreline. Additional costs are associated with drying and stabilization because natural solar drying is slow and weather-dependent, while

mechanical drying requires a large energy input [118]. High-value bioactive compound extraction incurs initial capital costs due to the need for specialized machinery, skilled labor, and controlled processing environments. In addition, regulatory compliance, such as testing for heavy metals, microplastics, pathogens, and polycyclic aromatic hydrocarbons, represents a recurring financial obligation that can be a barrier for small enterprises [119]. Profitability improves significantly when multiple co-products are produced from the same biomass stream, for example, polysaccharides for cosmetics, pigments for nutraceuticals, compost for agriculture, and biogas for energy generation. Thus, a multi-product biorefinery model, rather than a single-extract focus, is essential to maintain economic stability, manage seasonal variability in biomass supply, and ensure long-term commercial viability in regions affected by recurring seaweed influxes [120].

6. Future Research and Innovation Opportunities for BAS Recycling Combined with Modern Technologies

The future valorization of BAS could be integrated with modern technologies, including advanced analytical, green bioprocessing, and artificial intelligence (AI)-driven bioactive discovery to unlock new applications. These applications could also improve safety and standardization, transform this variable biomass into a reliable resource for high-value industries [121].

6.1. Precision Sorting and Contaminant Removal Technologies

Modern precision-sorting technologies significantly improve the safety and consistency of BAS by automating the detection and removal of contaminants. Optical and hyperspectral imaging systems can rapidly classify species, assess decomposition levels, and detect foreign materials [122]. AI-assisted sorting lines help eliminate plastics, stones, and sand, while water-jet or ultrasonic de-sanding units further reduce grit and microplastics. Together, these innovations enhance raw material purity, enabling more reliable downstream processing [123].

6.2. Metabolomics for the Discovery of Beach-Specific Bioactives

Detailed chemical profiling of beach-cast seaweeds is made possible by advanced metabolomics techniques like LC–MS/MS, GC–MS, NMR, and untargeted high-resolution mass spectrometry, which show degradation signatures, stress-induced metabolites, and newly generated chemicals. Metabolomics assists in distinguishing between native chemicals, environmental breakdown products, and microbial metabolites through spectrum annotation and comparative metabolite mapping. By directing focused extraction and valorization techniques, this method also makes it easier to find beach-specific bioactives with potential medicinal or cosmetic uses. Thus, the logical generation of bioactive libraries obtained from beach biomass is supported by metabolomics [124].

6.3. Microbial Fermentation and Co-Culture Bioprocessing

Stranded seaweed rapidly becomes a substrate for microbial colonization, initiating natural fermentation and co-metabolism processes that alter chemical composition. Controlled fermentation systems can replicate and improve upon the natural microbial degradation processes that occur on beaches. Lactic acid bacteria and marine Bacillus species convert polysaccharides into prebiotic oligosaccharides, while fungal co-cultures release bound phenolics and generate novel metabolic products. Engineered microbial strains can even produce specialized compounds such as phloroglucinol derivatives. These fermentation-based approaches create reproducible, standardized bioactive profiles from otherwise inconsistent beach biomass [125].

6.4. Robotic and Automated Collection Systems

Robotic and automated collection technologies streamline large-scale beach biomass removal while minimizing ecological disturbance. Drones and autonomous vehicles can map biomass distribution and estimate volume, while low-impact robotic harvesters collect seaweed without excessive sand removal. Sensors integrated into these systems monitor biomass decomposition stages in real time, enabling optimal harvesting decisions. This automation reduces labor costs and enhances environmental sustainability in BAS management [126].

6.5. AI and Machine Learning for Bioactive Predictions

Artificial intelligence and machine learning offer powerful tools for predicting bioactive potential in complex seaweed matrices, including those altered by environmental degradation. By integrating metabolomics profiles, environmental exposure data, and known bioactivity databases, AI models can identify promising compounds, predict synergistic interactions, and guide optimized extraction strategies. Machine learning algorithms can also forecast stability, toxicity, and degradation pathways, enabling faster and more efficient bioactive discovery. This data-driven approach accelerates the valorization of beach-cast seaweed by transforming chemical complexity into actionable insights for high-value product development [127].

6.6. Nanotechnology-Based Valorization

Nanotechnology enables the development of high-performance materials and delivery systems using seaweed-derived compounds. Fucoidan nanoparticles are promising for targeted drug delivery, while alginate-based nanofibers serve as scaffolds for tissue engineering and wound healing. Pigment-loaded nanoemulsions improve the stability and bioavailability of cosmetic ingredients. Through nano-encapsulation and nanoscale structuring, beach-cast seaweed components gain enhanced solubility, protection from degradation, and improved biological performance [128].

7. Conclusions

BAS is an unexplored biological resource as well as a serious environmental problem, necessitating a change from conventional disposal methods to integrated recycling and valorization techniques. Polysaccharides, phenolics, pigments, proteins, and lipids, all of which have potent bioactivities pertinent to a variety of industrial sectors, allow BAS to retain substantial biochemical value despite its degraded state. However, achieving this potential necessitates overcoming significant obstacles, such as inconsistent waste classification, heavy metal and microplastic contamination, high logistical costs, and a lack of standardized regulatory pathways for applications of food, cosmetic, or pharmaceutical grade. Coordinated policy changes, the creation of pre-treatment and biorefinery technologies, and enhanced quality-control frameworks designed especially for stranded biomass are all necessary to close these gaps. BAS can be transformed from an annoyance into a sustainable raw material stream by adopting a circular bioeconomy model. The transformation of BAS management into a system that promotes long-term sustainable development, economic resilience, and environmental protection ultimately depends on efficient governance, scientific innovation, and industry cooperation.

Author Contributions: Conceptualization, D.S.D.; methodology, D.S.D.; investigation, D.P.N.; resources, T.U.J.; writing—original draft preparation, D.S.D.; writing—review and editing, D.P.N. and T.U.J.; supervision, D.P.N. and T.U.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors utilized an AI-based language tool (ChatGPT 5.5, OpenAI) to assist with grammatical editing and language refinement during the preparation of this manuscript. The authors have carefully reviewed and verified all AI-assisted edits and take full responsibility for the accuracy, integrity, and originality of the content presented herein.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Smetacek, V.; Zingone, A. Green and golden seaweed tides on the rise. *Nature* **2013**, *504*, 84–88. [CrossRef] [PubMed]
2. Morand, P.; Merceron, M. Macroalgal Population and Sustainability. *J. Coast. Res.* **2005**, *21*, 1009–1020. [CrossRef]
3. Harb, T.B.; Chow, F. An overview of beach-cast seaweeds: Potential and opportunities for the valorization of underused waste biomass. *Algal Res.* **2022**, *62*, 102643. [CrossRef]
4. Mandalka, A.; Cavalcanti, M.I.L.G.; Harb, T.B.; Toyota Fujii, M.; Eisner, P.; Schweiggert-Weisz, U.; Chow, F. Nutritional Composition of Beach-Cast Marine Algae from the Brazilian Coast: Added Value for Algal Biomass Considered as Waste. *Foods* **2022**, *11*, 1201. [CrossRef] [PubMed]
5. Pardilhó, S.; Cotas, J.; Pereira, L.; Oliveira, M.B.; Dias, J.M. Marine macroalgae in a circular economy context: A comprehensive analysis focused on residual biomass. *Biotechnol. Adv.* **2022**, *60*, 107987. [CrossRef] [PubMed]
6. Rengasamy, K.R.R.; Mahomoodally, M.F.; Aumeeruddy, M.Z.; Zengin, G.; Xiao, J.; Kim, D.H. Bioactive compounds in seaweeds: An overview of their biological properties and safety. *Food Chem. Toxicol.* **2020**, *135*, 111013. [CrossRef] [PubMed]
7. Menaa, F.; Wijesinghe, P.A.U.I.; Thiripuranathar, G.; Uzair, B.; Iqbal, H.; Khan, B.A.; Menaa, B. Ecological and Industrial Implications of Dynamic Seaweed-Associated Microbiota Interactions. *Mar. Drugs* **2020**, *18*, 641. [CrossRef] [PubMed]
8. Liu, C.; Gao, J.; Jiang, H.; Sun, J.; Gao, X.; Mao, X. Value-added utilization technologies for seaweed processing waste in a circular economy: Developing a sustainable modern seaweed industry. *Compr. Rev. Food Sci. Food Saf.* **2024**, *23*, e70027. [CrossRef] [PubMed]
9. Rotini, A.; Chiesa, S.; Manfra, L.; Borrello, P.; Piermarini, R.; Silvestri, C.; Cappucci, S.; Parlagreco, L.; Devoti, S.; Pisapia, M.; et al. Effectiveness of the "Ecological Beach" Model: Beneficial Management of Posidonia Beach Casts and Banquette. *Water* **2020**, *12*, 3238. [CrossRef]
10. Wang, M.; Hu, C.; Barnes, B.B.; Mitchum, G.; Lapointe, B.; Montoya, J.P. The great Atlantic *Sargassum* belt. *Science* **2019**, *365*, 83–87. [CrossRef] [PubMed]
11. Rodríguez-Martínez, R.E.; Torres-Conde, E.G.; Rosellón-Druker, J.; Cabanillas-Terán, N.; Jáuregui-Haza, U. The Great Atlantic Sargassum Belt: Impacts on the Central and Western Caribbean—A review. *Harmful Algae* **2025**, *144*, 102838. [CrossRef] [PubMed]
12. Zhang, Y.; He, P.; Li, H.; Li, G.; Liu, J.; Jiao, F.; Zhang, J.; Huo, Y.; Shi, X.; Su, R.; et al. Ulva prolifera green-tide outbreaks and their environmental impact in the Yellow Sea, China. *Neurosurgery* **2019**, *6*, 825–838. [CrossRef] [PubMed]
13. Vance, C.; Mainardis, M.; Magnolo, F.; Sweeney, J.; Murphy, F. Modeling the effects of ecosystem changes on seagrass wrack valorization: Merging system dynamics with life cycle assessment. *J. Clean. Prod.* **2022**, *370*, 133454. [CrossRef]
14. Madejón, E.; Panettieri, M.; Madejón, P.; Pérez-de-Mora, A. Composting as Sustainable Managing Option for Seaweed Blooms on Recreational Beaches. *Waste Biomass Valorization* **2022**, *13*, 863–875. [CrossRef]
15. Coelho, F.P.; Barboza, M.G.; Guedes-Coelho, É.A.C.; Costa, M.M.d.S.; Santos, A.J.d.; Lima, M.F.d.; Silva, E.C.S.d.; Carneiro, V.A.R.; Soares, B.M.; França, E.J.d.; et al. Sustainability Of Beach Cast Seaweed Biomass For Biorefinary Process: Sampling Studies In The Littoral Of Alagoas/Brazil. *Rev. Contemp.* **2024**, *4*, e5306. [CrossRef]
16. Franzén, D.; Infantes, E.; Gröndahl, F. Beach-cast as biofertiliser in the Baltic Sea region-potential limitations due to cadmium-content. *Ocean Coast. Manag.* **2019**, *169*, 20–26. [CrossRef]
17. Rodríguez-Martínez, R.E.; Gómez Reali, M.Á.; Torres-Conde, E.G.; Bates, M.N. Temporal and spatial variation in hydrogen sulfide (H2S) emissions during holopelagic *Sargassum* spp. decomposition on beaches. *Environ. Res.* **2024**, *247*, 118235. [CrossRef] [PubMed]
18. Lymperatou, A.; Engelsen, T.K.; Skiadas, I.V.; Gavala, H.N. Different pretreatments of beach-cast seaweed for biogas production. *J. Clean. Prod.* **2022**, *362*, 132277. [CrossRef]
19. Warguła, Ł.; Wieczorek, B.; Kukla, M.; Krawiec, P.; Szewczyk, J.W. The Problem of Removing Seaweed from the Beaches: Review of Methods and Machines. *Water* **2021**, *13*, 736. [CrossRef]

20. Federigi, I.; Balestri, E.; Castelli, A.; De Battisti, D.; Maltagliati, F.; Menicagli, V.; Verani, M.; Lardicci, C.; Carducci, A. Beach pollution from marine litter: Analysis with the DPSIR framework (driver, pressure, state, impact, response) in Tuscany, Italy. *Ecol. Indic.* **2022**, *143*, 109395. [CrossRef]
21. Hanson, A.-M. Shoes in the seaweed and bottles on the beach. In *A Political Ecology of Women, Water and Global Environmental Change*; Buechler, S., Hanson, A.-M., Eds.; Routledge: New York, NY, USA, 2015; pp. 165–184.
22. Haro, S.; Morrison, L.; Caballero, I.; Figueroa, F.L.; Korbee, N.; Navarro, G.; Bermejo, R. Assessing Golden Tides from Space: Meteorological Drivers in the Accumulation of the Invasive Algae Rugulopteryx okamurae on Coasts. *Remote Sens.* **2024**, *16*, 2689. [CrossRef]
23. Seghetta, M.; Tørring, D.; Bruhn, A.; Thomsen, M. Bioextraction potential of seaweed in Denmark—An instrument for circular nutrient management. *Sci. Total Environ.* **2016**, *563–564*, 513–529. [CrossRef] [PubMed]
24. Morand, P.; Charlier, R.H.; Mazé, J. European bioconversion projects and realizations for macroalgal biomass: Saint-Cast-Le-Guildo (France) experiment. *Hydrobiologia* **1990**, *204*, 301–308. [CrossRef]
25. Shah, K.U.; McNeil, P. Management of a Changing Natural Environment: The Impact of Sargassum Seaweed in the Caribbean Using the Institutional Analysis and Design Framework. In *Pandemics, Disasters, Sustainability, Tourism: An Examination of Impact on and Resilience in Caribbean Small Island Developing States*; Bethell-Bennett, I., Rolle, S.A., Minnis, J., Okumus, F., Eds.; Emerald Publishing Limited: Leeds, UK, 2022. [CrossRef]
26. Cai, J.; Lovatelli, A.; Aguilar-Manjarrez, J.; Cornish, L.; Dabbadie, L.; Desrochers, A.; Diffey, S.; Garrido Gamarro, E.; Geehan, J.; Hurtado, A.; et al. *Seaweeds and Microalgae: An Overview for Unlocking Their Potential in Global Aquaculture Development*; FAO Fisheries and Aquaculture Circular No. 1229; FAO: Rome, Italy, 2021. [CrossRef]
27. Liranzo Gómez, R.E.; García-Cortés, D.; Jáuregui-Haza, U.J. Adaptation and Sustainable Management of Massive Influx of Sargassum in the Caribbean. 2021. Available online: https://procedia-esem.eu/pdf/issues/2021/no2/24_56_Liranzo-G%C3%B3mez_21.pdf (accessed on 4 June 2026).
28. Firoiu, D.; Ionescu, G.H.; Cismaș, C.M.; Costin, M.P.; Cismaș, L.M.; Ciobanu, Ș.C.F. Sustainable Production and Consumption in EU Member States: Achieving the 2030 Sustainable Development Goals (SDG 12). *Sustainability* **2025**, *17*, 1537. [CrossRef]
29. Duarte, C.M.; Agusti, S.; Barbier, E.; Britten, G.L.; Castilla, J.C.; Gattuso, J.-P.; Fulweiler, R.W.; Hughes, T.P.; Knowlton, N.; Lovelock, C.E.; et al. Rebuilding marine life. *Nature* **2020**, *580*, 39–51. [CrossRef] [PubMed]
30. Baker, S.; Constant, N.; Nicol, P. Oceans justice: Trade-offs between Sustainable Development Goals in the Seychelles. *Mar. Policy* **2023**, *147*, 105357. [CrossRef]
31. Rotter, A.; Barbier, M.; Bertoni, F.; Bones, A.M.; Cancela, M.L.; Carlsson, J.; Carvalho, M.F.; Cegłowska, M.; Chirivella-Martorell, J.; Conk Dalay, M.; et al. The Essentials of Marine Biotechnology. *Front. Mar. Sci.* **2021**, *8*, 629629. [CrossRef]
32. Rotter, A.; Bacu, A.; Barbier, M.; Bertoni, F.; Bones, A.M.; Cancela, M.L.; Carlsson, J.; Carvalho, M.F.; Cegłowska, M.; Dalay, M.C.; et al. A New Network for the Advancement of Marine Biotechnology in Europe and Beyond. *Front. Mar. Sci.* **2020**, *7*, 278. [CrossRef]
33. Almeida, M.; Vieira, H. Marine-Derived Collagen and Chitosan: Perspectives on Applications Using the Lens of UN SDGs and Blue Bioeconomy Strategies. *Mar. Drugs* **2025**, *23*, 318. [CrossRef] [PubMed]
34. Long, R. The Marine Strategy Framework Directive: A New European Approach to the Regulation of the Marine Environment, Marine Natural Resources and Marine Ecological Services. *J. Energy Nat. Resour. Law* **2011**, *29*, 1–44. [CrossRef]
35. Purcell-Meyerink, D.; Packer, M.A.; Wheeler, T.T.; Hayes, M. Aquaculture Production of the Brown Seaweeds Laminaria digitata and Macrocystis pyrifera: Applications in Food and Pharmaceuticals. *Molecules* **2021**, *26*, 1306. [CrossRef] [PubMed]
36. Hafting, J.T.; Craigie, J.S.; Stengel, D.B.; Loureiro, R.R.; Buschmann, A.H.; Yarish, C.; Edwards, M.D.; Critchley, A.T. Prospects and challenges for industrial production of seaweed bioactives. *J. Phycol.* **2015**, *51*, 821–837. [CrossRef] [PubMed]
37. Cotas, J.; Lomartire, S.; Gonçalves, A.M.M.; Pereira, L. From Ocean to Medicine: Harnessing Seaweed's Potential for Drug Development. *Int. J. Mol. Sci.* **2024**, *25*, 797. [CrossRef] [PubMed]
38. Lomartire, S.; Gonçalves, A.M.M. An Overview of Potential Seaweed-Derived Bioactive Compounds for Pharmaceutical Applications. *Mar. Drugs* **2022**, *20*, 141. [CrossRef] [PubMed]
39. Pardilhó, S.; Cotas, J.; Pacheco, D.; Gonçalves, A.M.M.; Bahcevandziev, K.; Pereira, L.; Figueirinha, A.; Dias, J.M. Valorisation of marine macroalgae waste using a cascade biorefinery approach: Exploratory study. *J. Clean. Prod.* **2023**, *385*, 135672. [CrossRef]
40. Galindo, A.; García, C.d.M.; Pérez, J.A.; Abdul-Jalbar, B.; Venuleo, M.; Acosta, N.G.; Marrero, M.; Rodríguez, C. Lipid Characterization of Beach-Cast Seaweeds from Gran Canaria Island: Potential Use in Human and Animal Nutrition. *J. Mar. Sci. Eng.* **2024**, *12*, 942. [CrossRef]
41. Yang, Y.; Zhang, M.; Alalawy, A.; Almutairi, F.; Al-Duais, M.; Wang, J.; Salama, E.-S. Identification and characterization of marine seaweeds for biocompounds production. *Environ. Technol. Innov.* **2021**, *24*, 101848. [CrossRef]
42. Smith, J.L.; Summers, G.; Wong, R. Nutrient and heavy metal content of edible seaweeds in New Zealand. *N. Z. J. Crop Hortic. Sci.* **2010**, *38*, 19–28. [CrossRef]

43. Venkatesan, J.; Lowe, B.; Anil, S.; Manivasagan, P.; Kheraif, A.A.A.; Kang, K.-H.; Kim, S.-K. Seaweed polysaccharides and their potential biomedical applications. *Starch-Stärke* **2015**, *67*, 381–390. [CrossRef]
44. Benalaya, I.; Alves, G.; Lopes, J.; Silva, L.R. A Review of Natural Polysaccharides: Sources, Characteristics, Properties, Food, and Pharmaceutical Applications. *Int. J. Mol. Sci.* **2024**, *25*, 1322. [CrossRef] [PubMed]
45. Nagahawatta, D.; Liyanage, N.; Jayawardena, T.U.; Yang, F.; Jayawardena, H.; Kurera, M.; Wang, F.; Fu, X.; Jeon, Y.-J. Functions and values of sulfated polysaccharides from seaweed. *Algae* **2023**, *38*, 217–240. [CrossRef]
46. Zheng, H.; Zhao, Y.; Guo, L. A Bioactive Substance Derived from Brown Seaweeds: Phlorotannins. *Mar. Drugs* **2022**, *20*, 742. [CrossRef] [PubMed]
47. Subbiah, V.; Ebrahimi, F.; Agar, O.T.; Legione, A.R.; Dunshea, F.R.; Barrow, C.J.; Suleria, H.A.R. Bioactive phenolic compounds from Australian seaweeds and their impact on gut health. *Sci. Rep.* **2025**, *15*, 20954. [CrossRef] [PubMed]
48. Rengasamy, K.R.R.; Amoo, S.O.; Aremu, A.O.; Stirk, W.A.; Gruz, J.; Šubrtová, M.; Doležal, K.; Van Staden, J. Phenolic profiles, antioxidant capacity, and acetylcholinesterase inhibitory activity of eight South African seaweeds. *J. Appl. Phycol.* **2015**, *27*, 1599–1605. [CrossRef]
49. Chen, Z.; Wu, W.; Wen, Y.; Zhang, L.; Wu, Y.; Farid, M.S.; El-Seedi, H.R.; Capanoglu, E.; Zhao, C. Recent advances of natural pigments from algae. *Food Prod. Process. Nutr.* **2023**, *5*, 39. [CrossRef]
50. Freitas, M.V.; Pacheco, D.; Cotas, J.; Mouga, T.; Afonso, C.; Pereira, L. Red Seaweed Pigments from a Biotechnological Perspective. *Phycology* **2022**, *2*, 1–29. [CrossRef]
51. Pereira, L.; Cotas, J.; Gonçalves, A.M. Seaweed Proteins: A Step towards Sustainability? *Nutrients* **2024**, *16*, 1123. [CrossRef] [PubMed]
52. Mišurcová, L.; Ambrožová, J.; Samek, D. Chapter 27—Seaweed Lipids as Nutraceuticals. *Adv. Food Nutr. Res.* **2011**, *64*, 339–355. [PubMed]
53. Kim, Y.R.; Park, S.-y.; Kim, J.Y. Therapeutic potential of seaweed extracts: In vitro and in vivo studies on alleviating inflammation and enhancing intestinal barrier function. *Food Biosci.* **2024**, *59*, 103774. [CrossRef]
54. Wang, L.; Jayawardena, T.U.; Yang, H.-W.; Lee, H.G.; Kang, M.-C.; Sanjeewa, K.K.A.; Oh, J.Y.; Jeon, Y.-J. Isolation, Characterization, and Antioxidant Activity Evaluation of a Fucoidan from an Enzymatic Digest of the Edible Seaweed, Hizikia fusiforme. *Antioxidants* **2020**, *9*, 363. [CrossRef] [PubMed]
55. Liyanage, N.M.; Nagahawatta, D.P.; Jayawardena, T.U.; Sanjeewa, K.K.A.; Jayawrdhana, H.H.A.C.K.; Kim, J.-I.; Jeon, Y.-J. Sulfated Polysaccharides from Seaweeds: A Promising Strategy for Combatting Viral Diseases—A Review. *Mar. Drugs* **2023**, *21*, 461. [CrossRef] [PubMed]
56. Shen, W.; Wang, H.; Guo, G.; Tuo, J. Immunomodulatory effects of Caulerpa racemosa var peltata polysaccharide and its selenizing product on T lymphocytes and NK cells in mice. *Sci. China Life Sci.* **2008**, *51*, 795–801. [CrossRef] [PubMed]
57. Lee, H.; Selvaraj, B.; Lee, J.W. Anticancer Effects of Seaweed-Derived Bioactive Compounds. *Appl. Sci.* **2021**, *11*, 11261. [CrossRef]
58. Gupta, V.; Kushwaha, H.R. Metabolic regulatory oscillations in intertidal green seaweed Ulva lactuca against tidal cycles. *Sci. Rep.* **2017**, *7*, 16430. [CrossRef] [PubMed]
59. Ahmad, T.; Eapen, M.S.; Ishaq, M.; Park, A.Y.; Karpiniec, S.S.; Stringer, D.N.; Sohal, S.S.; Fitton, J.H.; Guven, N.; Caruso, V.; et al. Anti-Inflammatory Activity of Fucoidan Extracts In Vitro. *Mar. Drugs* **2021**, *19*, 702. [CrossRef] [PubMed]
60. Friedman, A.J.; Phan, J.; Schairer, D.O.; Champer, J.; Qin, M.; Pirouz, A.; Blecher-Paz, K.; Oren, A.; Liu, P.T.; Modlin, R.L.; et al. Antimicrobial and Anti-Inflammatory Activity of Chitosan–Alginate Nanoparticles: A Targeted Therapy for Cutaneous Pathogens. *J. Investig. Dermatol.* **2013**, *133*, 1231–1239. [CrossRef] [PubMed]
61. Cindana Mo'o, F.R.; Wilar, G.; Devkota, H.P.; Wathoni, N. Ulvan, a Polysaccharide from Macroalga Ulva sp.: A Review of Chemistry, Biological Activities and Potential for Food and Biomedical Applications. *Appl. Sci.* **2020**, *10*, 5488. [CrossRef]
62. Khan, F.; Jeong, G.-J.; Khan, M.S.A.; Tabassum, N.; Kim, Y.-M. Seaweed-Derived Phlorotannins: A Review of Multiple Biological Roles and Action Mechanisms. *Mar. Drugs* **2022**, *20*, 384. [CrossRef] [PubMed]
63. Catarino, M.D.; Silva, A.M.S.; Cardoso, S.M. Fucaceae: A Source of Bioactive Phlorotannins. *Int. J. Mol. Sci.* **2017**, *18*, 1327. [CrossRef] [PubMed]
64. Lomartire, S.; Cotas, J.; Pacheco, D.; Marques, J.C.; Pereira, L.; Gonçalves, A.M.M. Environmental Impact on Seaweed Phenolic Production and Activity: An Important Step for Compound Exploitation. *Mar. Drugs* **2021**, *19*, 245. [CrossRef] [PubMed]
65. Černá, M. Chapter 24—Seaweed Proteins and Amino Acids as Nutraceuticals. *Adv. Food Nutr. Res.* **2011**, *64*, 297–312. [PubMed]
66. Lopes, D.; Rey, F.; Leal, M.C.; Lillebø, A.I.; Calado, R.; Domingues, M.R. Bioactivities of Lipid Extracts and Complex Lipids from Seaweeds: Current Knowledge and Future Prospects. *Mar. Drugs* **2021**, *19*, 686. [CrossRef] [PubMed]
67. Suzuki, T.; Ohsugi, Y.; Yoshie, Y.; Shirai, T.; Hirano, T. Dietary fiber content, water-holding capacity and binding capacity of seaweeds. *Fish. Sci. Res.* **1996**, *62*, 454–461. [CrossRef]
68. Hentati, F.; Tounsi, L.; Djomdi, D.; Pierre, G.; Delattre, C.; Ursu, A.V.; Fendri, I.; Abdelkafi, S.; Michaud, P. Bioactive Polysaccharides from Seaweeds. *Molecules* **2020**, *25*, 3152. [CrossRef] [PubMed]

69. Chen, B.; Li, Y.; Li, W.; Ye, S.; Zhu, L.; Ding, Y. Antitumor Activity and Mechanism of Terpenoids in Seaweeds Based on Literature Review and Network Pharmacology. *Adv. Biol.* **2024**, *8*, 2300541. [CrossRef] [PubMed]
70. Ghaliaoui, N.; Hazzit, M.; Mokrane, H. Seaweeds as a potential source of bioactive compounds. *Res. Biotechnol. Environ. Sci.* **2024**, *3*, 1–8. [CrossRef]
71. Seca, A.M.; Faustino, L.M.; Viveiros, M.M.; Rosa, G.P.; Barreto, M.d.C. Valorization of Macaronesia Beach-Cast Seaweeds: Secondary Metabolites and Antiaging Activity. In *Proceedings of the 14th Edition of the Nacional Organic Chemistry Meeting and 7th Edition of the Nacional Therapeutic Chemistry Meeting*; MDPI: Basel, Switzerland, 2022; pp. 95–96.
72. Attale, S.; Katuwavila, N. Nutritional and Functional Potential of *Laminaria* spp.: A Sustainable Marine Source of Essential Minerals and Bioactive Compounds. Transformative Applied Research 135. Available online: https://www.researchgate.net/profile/Kalni-Peiris/publication/402761954_Exploring_the_Drivers_of_Purchase_Intention_for_Activewear_among_Plus-Size_Consumers_in_Sri_Lanka/links/69bba3338c53216c011e618d/Exploring-the-Drivers-of-Purchase-Intention-for-Activewear-among-Plus-Size-Consumers-in-Sri-Lanka.pdf?__cf_chl_tk=dEuF9inRxi5qnd.yVrLaMlbh1nOA1efOK_CxAuxd4f4-1782456182-1.0.1.1-2T0_icjDeRSfejjvTqTqxQmgNq6V0wK_egvyiU8tj4I#page=162 (accessed on 4 June 2026).
73. Rudovica, V.; Rotter, A.; Gaudêncio, S.P.; Novoveská, L.; Akgül, F.; Akslen-Hoel, L.K.; Alexandrino, D.A.M.; Anne, O.; Arbidans, L.; Atanassova, M.; et al. Valorization of Marine Waste: Use of Industrial By-Products and Beach Wrack Towards the Production of High Added-Value Products. *Front. Mar. Sci.* **2021**, *8*, 723333. [CrossRef]
74. Michalak, I.; Wilk, R.; Chojnacka, K. Bioconversion of Baltic Seaweeds into Organic Compost. *Waste Biomass Valorization* **2017**, *8*, 1885–1895. [CrossRef]
75. Twigg, G.; Fedenko, J.; Hurst, G.; Stanley, M.S.; Hughes, A.D. A review of the current potential of European brown seaweed for the production of biofuels. *Energy Sustain. Soc.* **2024**, *14*, 21. [CrossRef]
76. Cárdenas-Aguiar, E.; Gascó, G.; Lado, M.; Méndez, A.; Paz-Ferreiro, J.; Paz-González, A. Characterization of Biochar from Beach-Cast Seaweed and Its Use for Amelioration of Acid Soils. *Land* **2024**, *13*, 881. [CrossRef]
77. Adinata, Y.; Panjaitan, T.S.S.; Firison, J.; Atmoko, B.A.; Krishna, N.H.; Sudrajad, P. From Shore to Farm: A Review of Macroalgae as A Sustainable Alternative Animal Feed in Indonesia. *Microbiol. Biotechnol. Lett.* **2025**, *53*, 22–29. [CrossRef]
78. Hofmann, L.C.; Strauss, S.; Shpigel, M.; Guttman, L.; Stengel, D.B.; Rebours, C.; Gjorgovska, N.; Turan, G.; Balina, K.; Zammit, G.; et al. The green seaweed Ulva: Tomorrow's "wheat of the sea" in foods, feeds, nutrition, and biomaterials. *Crit. Rev. Food Sci. Nutr.* **2025**, *65*, 3728–3763. [CrossRef] [PubMed]
79. Zárate, R.; Portillo, E.; Teixidó, S.; Carvalho, M.A.A.P.d.; Nunes, N.; Ferraz, S.; Seca, A.M.L.; Rosa, G.P.; Barreto, M.C. Pharmacological and Cosmeceutical Potential of Seaweed Beach-Casts of Macaronesia. *Appl. Sci.* **2020**, *10*, 5831. [CrossRef]
80. Perera, K.Y.; Sharma, S.; Pradhan, D.; Jaiswal, A.K.; Jaiswal, S. Seaweed Polysaccharide in Food Contact Materials (Active Packaging, Intelligent Packaging, Edible Films, and Coatings). *Foods* **2021**, *10*, 2088. [CrossRef] [PubMed]
81. Malektaj, H.; Drozdov, A.D.; de Claville Christiansen, J. Mechanical Properties of Alginate Hydrogels Cross-Linked with Multivalent Cations. *Polymers* **2023**, *15*, 3012. [CrossRef] [PubMed]
82. Oliveira, C.; Gonçalves, C.S.; Martins, E.P.; Neves, N.M.; Reis, R.L.; Costa, B.M.; Silva, T.H.; Martins, A. Fucoidan/chitosan nanoparticles functionalized with anti-ErbB-2 target breast cancer cells and impair tumor growth in vivo. *Int. J. Pharm.* **2021**, *600*, 120548. [CrossRef] [PubMed]
83. Devi, G.V.Y.; Nagendra, A.H.; Shenoy, P.S.; Chatterjee, K.; Venkatesan, J. Fucoidan-Incorporated Composite Scaffold Stimulates Osteogenic Differentiation of Mesenchymal Stem Cells for Bone Tissue Engineering. *Mar. Drugs* **2022**, *20*, 589. [CrossRef] [PubMed]
84. Ghahtan, N.; Dehghan, N.; Ullah, M.; Khoradmehr, A.; Habibi, H.; Nabipour, I.; Baghban, N. From seaweed to healing: The potential of fucoidan in wound therapy. *Nat. Prod. Res.* **2025**, *39*, 1345–1358. [CrossRef] [PubMed]
85. Mendis, E.; Kim, S.-K. Chapter 1—Present and Future Prospects of Seaweeds in Developing Functional Foods. *Adv. Food Nutr. Res.* **2011**, *64*, 1–15. [PubMed]
86. Lourenço-Lopes, C.; Garcia-Oliveira, P.; Carpena, M.; Fraga-Corral, M.; Jimenez-Lopez, C.; Pereira, A.G.; Prieto, M.A.; Simal-Gandara, J. Scientific Approaches on Extraction, Purification and Stability for the Commercialization of Fucoxanthin Recovered from Brown Algae. *Foods* **2020**, *9*, 1113. [CrossRef] [PubMed]
87. Iqbal, M.W.; Riaz, T.; Mahmood, S.; Bilal, M.; Manzoor, M.F.; Qamar, S.A.; Qi, X. Fucoidan-based nanomaterial and its multifunctional role for pharmaceutical and biomedical applications. *Crit. Rev. Food Sci. Nutr.* **2024**, *64*, 354–380. [CrossRef] [PubMed]
88. Pereira, L. Seaweeds as Source of Bioactive Substances and Skin Care Therapy—Cosmeceuticals, Algotheraphy, and Thalassotherapy. *Cosmetics* **2018**, *5*, 68. [CrossRef]
89. Milledge, J.J.; Harvey, P.J. Golden Tides: Problem or Golden Opportunity? The Valorisation of Sargassum from Beach Inundations. *J. Mar. Sci. Eng.* **2016**, *4*, 60. [CrossRef]
90. Saboor, F.H.; Hadian-Ghazvini, S.; Torkashvand, M. Microplastics in aquatic environments: Recent advances in separation techniques. *Period. Polytech. Chem. Eng.* **2022**, *66*, 167–181. [CrossRef]

91. Sanjeewa, K.K.A.; Herath, K.H.I.N.M.; Kim, Y.-S.; Jeon, Y.-J.; Kim, S.-K. Enzyme-assisted extraction of bioactive compounds from seaweeds and microalgae. *Trends Anal. Chem.* **2023**, *167*, 117266. [CrossRef]
92. Dessle, F. Harvesting and Utilizing Beach Cast on Gotland: A Study of the Benefits, Challenges and Opportunities of Turning a Waste into a Resource. Master's Thesis, KTH Royal Institute of Technology, School of Architecture and the Built Environment, Stockholm, Sweden, 2017.
93. Wijesinghe, W.A.J.P.; Jeon, Y.-J. Enzyme-assistant extraction (EAE) of bioactive components: A useful approach for recovery of industrially important metabolites from seaweeds: A review. *Fitoterapia* **2012**, *83*, 6–12. [CrossRef] [PubMed]
94. Bhadange, Y.A.; Carpenter, J.; Saharan, V.K. A Comprehensive Review on Advanced Extraction Techniques for Retrieving Bioactive Components from Natural Sources. *ACS Omega* **2024**, *9*, 31274–31297. [CrossRef] [PubMed]
95. Khammassi, H.; Bouaziz, T.; Dammak, M.; Dubesay, P.; Pierre, G.; Michaud, P.; Abdelkafi, S. Brown Algae-Derived Polysaccharides: From Sustainable Bioprocessing to Industrial Applications. *Polysaccharides* **2026**, *7*, 10. [CrossRef]
96. Xiao, Q.; Fan, X. The Guideline for the Extraction, Purification and Structural Characterization of Sulfated Polysaccharides From Macroalgae. *Food Chem.* **2025**, *1*, 61–71. [CrossRef]
97. Chadwick, M.; Carvalho, L.G.; Vanegas, C.; Dimartino, S. A Comparative Review of Alternative Fucoidan Extraction Techniques from Seaweed. *Mar. Drugs* **2025**, *23*, 27. [CrossRef] [PubMed]
98. Santos, S.A.O.; Félix, R.; Pais, A.C.S.; Rocha, S.M.; Silvestre, A.J.D. The Quest for Phenolic Compounds from Macroalgae: A Review of Extraction and Identification Methodologies. *Biomolecules* **2019**, *9*, 847. [CrossRef] [PubMed]
99. Aryee, A.N.A.; Agyei, D.; Akanbi, T.O. Recovery and utilization of seaweed pigments in food processing. *Curr. Opin. Food Sci.* **2018**, *19*, 113–119. [CrossRef]
100. Kadam, S.U.; Tiwari, B.K.; Smyth, T.J.; O'Donnell, C.P. Optimization of ultrasound assisted extraction of bioactive components from brown seaweed Ascophyllum nodosum using response surface methodology. *Ultrason. Sonochem.* **2015**, *23*, 308–316. [CrossRef] [PubMed]
101. Dhayalan, M.; Phanumartwiwath, A. Ultrasound-assisted extraction of proteins and polysaccharides from seaweed: A comprehensive review of optimization strategies, comparative analysis and future perspectives. *Algal Res.* **2025**, *90*, 104136. [CrossRef]
102. Rodriguez-Jasso, R.M.; Mussatto, S.I.; Pastrana, L.; Aguilar, C.N.; Teixeira, J.A. Microwave-assisted extraction of sulfated polysaccharides (fucoidan) from brown seaweed. *Carbohydr. Polym.* **2011**, *86*, 1137–1144. [CrossRef]
103. Perez-Vazquez, A.; Carpena, M.; Barciela, P.; Cassani, L.; Simal-Gandara, J.; Prieto, M.A. Pressurized Liquid Extraction for the Recovery of Bioactive Compounds from Seaweeds for Food Industry Application: A Review. *Antioxidants* **2023**, *12*, 612. [CrossRef] [PubMed]
104. Schechtman, L.M. The Safety Assessment Process—Setting the Scene: An FDA Perspective. *ILAR J.* **2002**, *43*, S5–S10. [CrossRef] [PubMed]
105. Hwang, Y.O.; Park, S.G.; Park, G.Y.; Choi, S.M.; Kim, M.Y. Total arsenic, mercury, lead, and cadmium contents in edible dried seaweed in Korea. *Food Addit. Contam. Part B Surveill.* **2010**, *3*, 7–13. [CrossRef] [PubMed]
106. Zothanpuii, F.; Rajesh, R.; Selvakumar, K. A review on stability testing guidelines of pharmaceutical products. *Asian J. Pharm. Clin. Res.* **2020**, *13*, 3–9. [CrossRef]
107. Ali, D.S.; Elfalleh, W.; Smaoui, S. Nutraceutical and functional foods: Developmental of toxicity testing and safety assessment. *Euro-Mediterr. J. Environ. Integr.* **2025**, *10*, 3489–3506. [CrossRef]
108. Das, A.; Sen, C.K. Chapter 2—Nutritional Supplements and Functional Foods: Functional Significance and Global Regulations. In *Nutraceutical and Functional Food Regulations in the United States and Around the World*, 2nd ed.; Bagchi, D., Ed.; Academic Press: San Diego, CA, USA, 2014; pp. 13–39. [CrossRef]
109. Ferreira, M.; Matos, A.; Couras, A.; Marto, J.; Ribeiro, H. Overview of Cosmetic Regulatory Frameworks around the World. *Cosmetics* **2022**, *9*, 72. [CrossRef]
110. Basu, S.B.; Gupta, A.D.; Ecks, S.; Jeffery, P.; Jeffery, R.; Singh, N.; Subedi, M.S. Good Manufacturing Practice in the Pharmaceutical Industry. 2007. Available online: https://assets.publishing.service.gov.uk/media/57a08bf9e5274a31e0000eee/60336-WP3.pdf (accessed on 4 June 2026).
111. Jacquemin, L.; Pontalier, P.-Y.; Sablayrolles, C. Life cycle assessment (LCA) applied to the process industry: A review. *Int. J. Life Cycle Assess.* **2012**, *17*, 1028–1041. [CrossRef]
112. Giacomella, L. Techno-Economic Assessment (TEA) and Life Cycle Costing Analysis (LCCA): Discussing methodological steps and integrability. *Insights Reg. Dev.* **2021**, *3*, 176–197. [CrossRef] [PubMed]
113. Mahmud, R.; Moni, S.M.; High, K.; Carbajales-Dale, M. Integration of techno-economic analysis and life cycle assessment for sustainable process design—A review. *J. Clean. Prod.* **2021**, *317*, 128247. [CrossRef]
114. Fomo, G.; Madzimbamuto, T.N.; Ojumu, T.V. Applications of Nonconventional Green Extraction Technologies in Process Industries: Challenges, Limitations and Perspectives. *Sustainability* **2020**, *12*, 5244. [CrossRef]
115. Nilsson, A.E.; Bergman, K.; Gomez Barrio, L.P.; Cabral, E.M.; Tiwari, B.K. Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy. *Algal Res.* **2022**, *65*, 102725. [CrossRef]

116. Nedumaran, T. Seaweed: A Fertilizer for Sustainable Agriculture. In *Sustainable Agriculture Towards Food Security*; Dhanarajan, A., Ed.; Springer: Singapore, 2017; pp. 159–174. [CrossRef]
117. Rahaman, A.; Kumari, A.; Zeng, X.-A.; Korin, A.; Khalifa, I.; Maqsood, S. Processing of Marine Derived By-Products and Their Applications: A Review. *Waste Biomass Valorization* **2025**, *17*, 2525–2541. [CrossRef]
118. Charoensiddhi, S.; Lorbeer, A.J.; Franco, C.M.M.; Su, P.; Conlon, M.A.; Zhang, W. Process and economic feasibility for the production of functional food from the brown alga Ecklonia radiata. *Algal Res.* **2018**, *29*, 80–91. [CrossRef]
119. Nazemi, F.; Karimi, K.; Denayer, J.F.M.; Shafiei, M. Techno-economic aspects of different process approaches based on brown macroalgae feedstock: A step toward commercialization of seaweed-based biorefineries. *Algal Res.* **2021**, *58*, 102366. [CrossRef]
120. Border, A.F. *Techno-Economic Analysis of Seaweed Biorefinery Scenarios for Production of High-Value Products and Biogas*; Stellenbosch University: Stellenbosch, South Africa, 2020.
121. Duan, F.-L.; Duan, C.-B.; Xu, H.-L.; Zhao, X.-Y.; Sukhbaatar, O.; Gao, J.; Zhang, M.-Z.; Zhang, W.-H.; Gu, Y.-C. AI-driven drug discovery from natural products. *Adv. Agrochem* **2024**, *3*, 185–187. [CrossRef]
122. Lodhi, V.; Chakravarty, D.; Mitra, P. Hyperspectral Imaging System: Development Aspects and Recent Trends. *Sens. Imaging* **2019**, *20*, 35. [CrossRef]
123. Selvaraj, V.; Min, S. AI-assisted monitoring of human-centered assembly: A comprehensive review. *Int. J. Precis. Eng. Manuf.* **2023**, *1*, 201–218. [CrossRef]
124. Farag, M.A.; Porzel, A.; Wessjohann, L.A. Comparative metabolite profiling and fingerprinting of medicinal licorice roots using a multiplex approach of GC–MS, LC–MS and 1D NMR techniques. *Phytochemistry* **2012**, *76*, 60–72. [CrossRef] [PubMed]
125. Sørensen, H.M.; Rochfort, K.D.; Maye, S.; MacLeod, G.; Brabazon, D.; Loscher, C.; Freeland, B. Exopolysaccharides of Lactic Acid Bacteria: Production, Purification and Health Benefits towards Functional Food. *Nutrients* **2022**, *14*, 2938. [CrossRef] [PubMed]
126. Hardy, H.; van Walsum, M.; Livermore, L.; Walton, S. Research and development in robotics with potential to automate handling of biological collections. *Res. Ideas Outcomes* **2020**, *6*, e61366. [CrossRef]
127. Prajapati, P.; Shrivastav, P.; Prajapati, J.; Prajapati, B. Deep Learning Approaches for Predicting Bioactivity of Natural Compounds. *J. Nat. Prod.* **2025**, *16*, e22103155332267. [CrossRef]
128. Geetha Bai, R.; Sudheer, S.; Premarathna, A.D.; Tuvikene, R. Marine Macroalgal Polysaccharides in Nanomedicine: Blue Biotechnology Contributions in Advanced Therapeutics. *Molecules* **2026**, *31*, 175. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.