Green Extraction Techniques for Phenolic-rich Marine Algae for Food Applications: A Systematic Literature Review

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***Abstract*—Marine and freshwater algae are emerging as sustainable sources of phenolic compounds and other bioactives for food and health applications. This systematic review evaluates 43 studies on phenolic-rich extracts from marine, coastal, and freshwater algae, focusing on species and phenolic profiles, extraction techniques, and antioxidant and health-related functions in food and digestion-related contexts. Green, red, and brown taxa provide substantial phenolic contents, including plant-like phenolic acids and flavonoids as well as marine-specific phlorotannins, often co-extracted with polysaccharides, proteins, pigments, and minerals that shape extract functionality. Conventional hydro-organic solid-liquid extraction remains the dominant method but is limited by long extraction times, high solvent use, and only partial alignment with green-processing principles, whereas ultrasound-assisted, microwave-assisted, subcritical-water, and hybrid techniques can achieve similar or higher phenolic yields more efficiently, depending on species and matrix. Across studies, higher phenolic or phlorotannin contents generally correspond to stronger antioxidant responses and, in some cases, anti-inflammatory, metabolic, anticancer, or antimicrobial activities, while evidence from in vitro digestion and in vivo models highlights gastrointestinal fate and microbiota interactions as key determinants of efficacy and supports the need for integrated green-extraction and delivery-system strategies for clean-label functional foods.**

***Keywords*—phenolic compound, antioxidant activity, functional foods, green extraction**

I. Introduction

Marine and freshwater algae have gained increasing attention as sustainable sources of phenolic compounds and other bioactive constituents that are highly relevant for food and health applications [1]. Brown seaweeds, in particular, often exhibit high levels of phlorotannins and other phenolics, while red and green macroalgae and selected freshwater species also contribute meaningful phenolic profiles together with polysaccharides, proteins, lipids, and minerals [2]. Species such as *E. radiata*, *S. wightii*, *Gracilariopsis* spp., *C. racemosa*, *C. lentillifera*, *U. intestinalis*, and *Spirogyra* show substantial total phenolic contents with strong in vitro antioxidant activities, indicating potential as multifunctional ingredients for functional foods and nutraceuticals [3]. Additional phytochemical and antioxidant studies on marine macroalgae show diverse phenolic and terpenoid profiles with strong radical-scavenging capacity, reinforcing algae as rich antioxidant sources for food and health applications [4].

Beyond acting as chemical antioxidants, phenolic-rich algal extracts and related bioactive fractions exhibit a broad range of biological activities that are highly relevant to chronic disease prevention [5]. Extracts from green, red, and brown algae can inhibit key enzymes related to obesity and glucose homeostasis, modulate inflammatory markers, exert cytotoxic effects on tumor cells, and inhibit pathogenic microorganisms [3]. Phenolic-rich extracts from *Caulerpa racemosa* and *Caulerpa lentillifera* show anti-obesogenic and anti-diabetic effects, while preparations from brown and red algae, including metal or silver nanoparticles, display in vitro anticancer and antimicrobial activities [6]. Parallel studies incorporating algal phenolic extracts into model foods such as oil-in-water emulsions and marine products, and testing them under simulated gastrointestinal digestion, have begun to link extraction strategy and matrix composition with oxidative stability and bioaccessibility of algal bioactives [7].

Conventional solid-liquid methods such as maceration and Soxhlet, widely used to recover phenolic compounds and other bioactives from marine and freshwater algae, often require long extraction times, high temperatures, and large solvent-to-solid ratios, increasing energy and solvent use and risking degradation or structural changes of thermolabile phenolics and phlorotannins [8]. Recent research in green processing has developed more efficient extraction technologies for algal biomass, with ultrasound-assisted extraction often giving equal or higher phenolic and sulfated polysaccharide yields in shorter times using greener solvents than conventional maceration [8]. Pressurized or alkaline subcritical-water extraction uses tunable hot water to solubilize phenolics and co-extracted compounds while reducing the need for large volumes of organic solvents [9]. Studies on sulfated polysaccharide recovery, sustainable and novel extraction approaches, and alternative solvents such as natural deep eutectic systems highlight a broad toolbox of green extraction strategies that can be adapted to phenolic-rich algal biomass [10].

At the same time, growing evidence indicates that extraction performance and the functionality of algal extracts are strongly influenced by matrix effects and interactions among co-extracted components [11]. Studies on marine algal polysaccharides show that sulfated polysaccharides from brown, red, and green algae are structurally diverse and bioactive, and that non-covalent complexes with phenolics in brown seaweeds can modify apparent antioxidant capacity and phenolic stability [12]. Studies on crude sulfated polysaccharides, algae-based foods, and lipid bioaccessibility show that digestion behavior and health functionality depend not only on total phenolic content but also on how phenolics, polysaccharides, and other macromolecules are structurally organized in the extract or food matrix [13]. A focused systematic synthesis is still lacking that jointly addresses which marine, coastal, and freshwater algae are richest in phenolics, how conventional and green extraction techniques perform on these matrices, and how the resulting extracts behave in food and digestion-related contexts regarding antioxidant activity, bioaccessibility, and health effects [14]. Sea grapes (*Caulerpa* sp.) are of significant interest due to their phenolic richness and growing consumption as edible vegetables in Asia (Fig. 1). Recent studies further explore how digestive processes affect their antioxidant bioaccessibility, emphasizing the link between extraction efficiency and post-digestion functionality.

Fig. 1. *Caulerpa lentillifera* (sea grapes).

II. Materials and Methods

A. Literature Search Strategy

A systematic literature search was conducted using Scopus, Web of Science, ScienceDirect, and PubMed to identify peer-reviewed studies on phenolic-rich or phenolic-containing extracts from marine, coastal, and freshwater algae relevant to food and health applications. The search used combinations of keywords related to algal biomass, phenolic compounds, extraction techniques, and functional food or digestion-related applications. Only original research articles published between 2016 and 2025 were considered. Titles and abstracts were first screened for relevance, followed by full-text evaluation. Reference lists of selected articles were also examined to identify additional eligible studies. In total, 43 primary research articles met the inclusion criteria and were included in the qualitative synthesis.

B. Study Selection and Eligibility Criteria

Study selection was conducted in two stages: title and abstract screening followed by full-text assessment using predefined inclusion and exclusion criteria. Studies were included if they investigated marine or freshwater algae as the primary biomass, applied phenolic-targeted extraction methods with sufficient methodological detail, and reported phenolic composition, antioxidant capacity, or other relevant bioactivities for food and health applications. Studies were excluded if they did not involve algal phenolics, were non-primary literature, focused exclusively on polysaccharides or lipids, or lacked sufficient methodological information for reliable data extraction.

C. Study Selection Flow (PRISMA)

The study selection followed PRISMA, progressing through identification, screening, eligibility, and inclusion stages. After duplicates were removed, 260 unique records were screened, and 197 that did not meet the inclusion criteria based on titles and abstracts were excluded.

Full texts of the remaining 63 articles were assessed against the eligibility criteria, and 20 that lacked phenolic-focused extractions, sufficient methodological detail, or application to algal extracts were excluded. In total, 43 primary research articles met all criteria and were included in the qualitative synthesis, as summarized in the PRISMA flow diagram (Fig. 2).

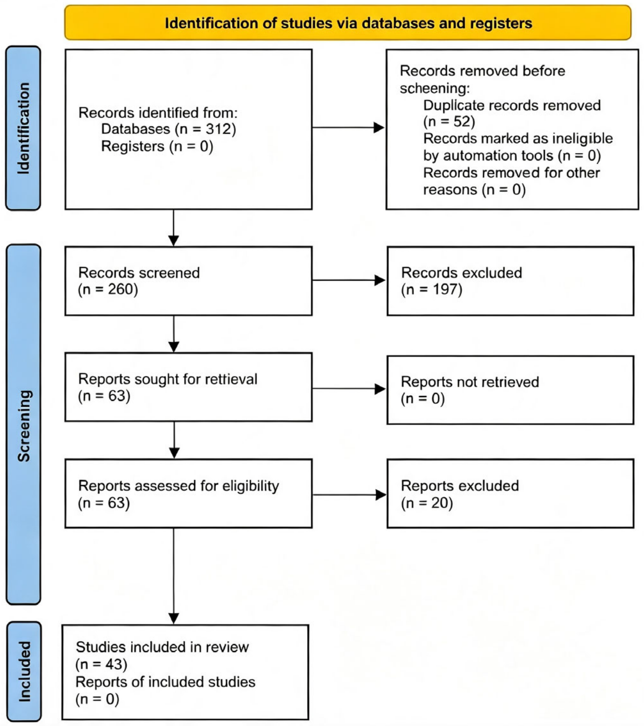

Fig. 2. PRISMA flow diagram of study selection.

D. Data Extraction and Synthesis

Data from the 43 included studies were extracted into a predefined spreadsheet covering algal species, targeted fractions, extraction techniques and key processing parameters, phenolic characterization, antioxidant assays, reported bioactivities, and applications in food or digestion-related systems. Information on interactions between phenolics and other matrix components (e.g., polysaccharides and proteins) was also recorded to interpret matrix effects on extraction efficiency, antioxidant capacity, and phenolic stability. The extracted data were then synthesized narratively into three thematic areas: phenolic-rich algal species and their phenolic profiles, conventional and green extraction techniques, and antioxidant and health-related functionalities.

E. Classification of Extraction Techniques

Extraction approaches were classified into Ultrasound-Assisted Extraction (UAE), Microwave-Assisted Extraction (MAE), and alkaline subcritical-water extraction, representing the most commonly applied green technologies for phenolic-rich algal biomass. These methods were evaluated based on their operational principles, matrix interactions, and reported effects on phenolic recovery, antioxidant activity, and functional performance in food and digestion-related systems. A schematic overview of the various extraction techniques and their operational frameworks is presented in Fig. 3. This illustration highlights key process differences and similarities between conventional and advanced methods. Visualizing these pathways allows for a more effective analysis of the parameters influencing the yield and purity of the bioactive compounds.

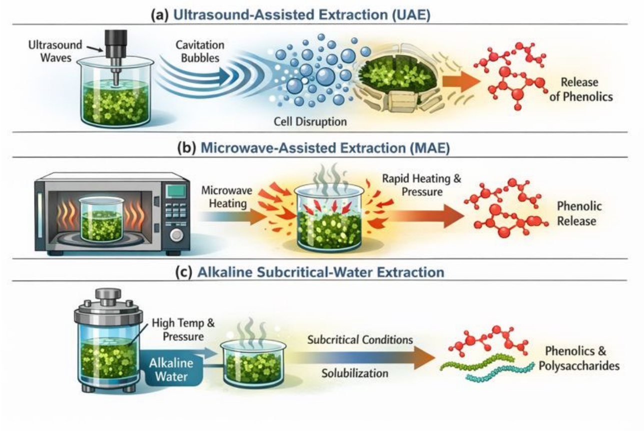

Fig. 3. Schematic overview of green extraction techniques.

III. Results and Discussion

A. Phenolic-rich Algae and Phenolic Profiles

The 43 included studies confirm that marine and freshwater algae are important reservoirs of phenolic-rich biomass, spanning green, brown, and red taxa alongside selected non-algal comparators. They report substantial total phenolic contents and diverse profiles ranging from simple phenolic acids and flavonoids to phlorotannins and phenolic-polysaccharide complexes that underpin the observed antioxidant and health-related activities [15]. Green and red algae tend to be richer in 'classical' plant-like phenolics, while brown algae characteristically accumulate phlorotannins, a unique class of marine-specific polyphenols derived from phloroglucinol units [16]. Building on these observations, the main characteristics of the 43 included studies, including algal species, extraction techniques, and key phenolic-related outcomes, are summarized in Table 1.

The summary of Table 1 also shows that phenolic profiles are strongly species- and matrix-dependent, even under broadly similar extraction conditions [17]. Brown algae such as Sargassum wightii and Ecklonia radiata consistently yield complex phlorotannin mixtures that are closely linked to high *in vitro* antioxidant capacity and, in some cases, additional biological activities such as enzyme inhibition or cytotoxicity toward cancer cells [18]. In contrast, green and freshwater taxa like Ulva intestinalis and Spirogyra sp. often exhibit more moderate total phenolic levels but still contribute meaningful antioxidant and antimicrobial functions [19].

Another key pattern emerging from the 43 studies is the close relationship between phenolic content, structural diversity, and measured bioactivities [7]. Extracts with higher total phenolics or enriched phlorotannin fractions generally show stronger radical-scavenging and reducing power in standard antioxidant assays, while certain phenolic-rich preparations display additional anti-inflammatory, antitumor, anti-obesogenic, or anti-diabetic effects in cell-based and *in vivo* models [20]. Nonetheless, some studies report discrepancies where moderate phenolic levels still correspond to robust biological responses, highlighting the likely contribution of synergistic interactions between phenolics, polysaccharides, and other co-extracted constituents [21]. A substantial fraction of the studies quantify only total phenolics using colorimetric assays without detailed ographic identification, and methodological differences in extraction solvents, expression units, and reference standards complicate comparisons across laboratories [22].

Table 1. Summary of extraction techniques

Species (Group)	Technique	Main Outcomes
Various marine algae	Ultrasound-assisted extraction vs conventional	Higher yield, faster extraction, less solvent
Chaetomorpha sp. (green)	Conventional solvent extraction of dried biomass	Antioxidant and anticancer extract
Enteromorpha prolifera (green)	Various extraction techniques for polysaccharides	Anti-oxidant, anti-inflammatory and other health-related activities of polysaccharides
Beachcast brown algae (brown)	Conventional solvent extraction of beachcast biomass	Phenolic-rich extracts with notable antioxidant capacity
Various marine algae polysaccharides	Extraction of sulfated polysaccharides and crude extracts	Anti-inflammatory and protective effects in intestinal disease models
Brown algae (*Phaeophyceae*)	Solvent extraction, identification and quantification of phenolics	High phenolic contents with strong antioxidant potential
Caulerpa lentillifera + *Kappa phycus alvarezii*	Solvent extraction (metanol/etanol); phytochemical screening	Longlines maximized *K. alvarezii* growth, while *C. lentillifera* performed best in plastic cages
Various marine algae polysaccharides	Isolation and structural characterization of algal polysaccharides	Reported antioxidant, immunomodulatory and other bioactivities
Various marine algae (sulfated polysaccharides)	Conventional vs ultrasound-assisted extraction optimization	UAE improves yield/efficiency of sulfated polysaccharides
Caulerpa racemosa (green, Indonesian)	Extraction and characterization of bioactive fractions as functional food candidate	Antioxidant, anti-obesity and metabolic health-related activities
Red macroalgae (various species)	Comprehensive phenolic profiling and antioxidant assays	High phenolic diversity with strong antioxidant capacity
Crude sulfated polysaccharides from marine algae	*in vitro* and *in silico* antioxidant assessment	Notable radical-scavenging capacity and predicted interaction with oxidative-stress targets
Gracilariopsis sp. (red)	Proximate and phenolic analysis of dried samples	Provides nutritional profile and measurable phenolic content with antioxidant potential
Enteromorpha intestinalis (green)	Extraction and characterization of phenolic compounds	Identifies algal phenolics and reports notable antioxidant and bioactive effects

B. Conventional Versus Green Extraction Techniques

Conventional extraction of phenolic-rich marine algae mainly relies on solid-liquid extraction using hydro-organic solvents (typically aqueous methanol or ethanol), maceration, heating, and Soxhlet extraction, which are simple but time-consuming and solvent-intensive [8]. Extraction of bioactives from beach-cast brown algae via hot ethanol or acetone likewise demonstrates good recovery but highlights the drawbacks of long extraction time and limited alignment with green chemistry principles [23]. To address these limitations, several green extraction technologies have been developed, notably Ultrasound-Assisted Extraction (UAE), Microwave-Assisted Extraction (MAE), and alkaline subcritical-water extraction, often applied alone or in sequence [10]. UAE exploits acoustic cavitation to disrupt cell walls, increase solvent penetration, and accelerate mass transfer, which typically allows similar or higher yields of phenolics, sulfated polysaccharides, or pigments in minutes instead of hours, using lower amounts of Generally Recognized As Safe (GRAS) solvents [24]. Several studies also report that green extraction techniques may offer improved cost-effectiveness compared with conventional solvent extraction, mainly due to reduced solvent consumption, shorter extraction time, and lower overall energy requirements. Although the initial investment for specialized equipment such as ultrasonic or microwave systems can be relatively high, operational costs may decrease over time because of higher extraction efficiency and reduced solvent usage.

Comparative studies show that no single extraction method is universally superior, and performance depends strongly on species, target compounds, and processing conditions [8]. Ultrasound- and microwave-assisted extraction are commonly applied as process-intensification techniques that enhance mass transfer between the solvent and algal biomass. Most laboratory-scale studies implement these techniques in batch systems to stimulate cell disruption and accelerate compound diffusion. Continuous or semi-continuous extraction configurations are increasingly explored for industrial applications, particularly when higher processing capacity and process integration are required. For instance, combining conventional solid-liquid extraction with UAE significantly improved the recovery of sulfated polysaccharides from several marine algae compared with either method alone, while still reducing solvent and time requirements relative to purely conventional protocols [24]. In most cases, green techniques such as UAE, MAE, and subcritical-water extraction are therefore considered more suitable for the sustainable development of phenolic-rich functional ingredients from marine algae, especially when scaled toward industrial applications and life-cycle impacts are taken into account [10].

Green extraction techniques also enable multi-factor optimization to balance phenolic yield, energy consumption, and final product quality. Several studies using response surface-based experimental designs show that variables such as solvent-to-solid ratio, ultrasonic intensity or microwave power, temperature, and solvent pH can be modelled to maximize total phenolics while minimizing thermal degradation and the use of organic solvents [25]. This approach aligns with green-chemistry principles because it promotes more efficient, scalable conditions and supports regulatory compliance when food-grade solvents (for example, ethanol-water mixtures) are used as the main extraction phase [26].

In addition, combined (hybrid) techniques are increasingly explored to enhance the efficiency of phenolic recovery from different algal groups (brown, red, and green species) [27]. Integrating MAE or UAE with high-pressure methods such as pressurized liquid extraction or subcritical-water extraction has been reported to improve solvent diffusion into the cell matrix, facilitate the release of cell-wall-bound phenolics, and shorten extraction time without compromising the antioxidant activity of the extracts [28]. Such hybrid approaches are promising for industrial development because they merge the advantages of individual techniques while reducing environmental footprint and long-term operating costs [29].

C. Antioxidant and Health-Related Activities

Brown macroalgae are important dietary sources of natural antioxidants due to their high contents of phenolic compounds (especially phlorotannins), sulfated polysaccharides, carotenoids, and vitamins. Extracts from genera such as *Sargassum*, *Fucus*, *Ecklonia*, and *Undaria* show strong radical-scavenging capacity in standard antioxidant assays, often comparable to or exceeding synthetic antioxidants, supporting their use as raw materials for functional foods and nutraceuticals targeting oxidative stress [2]. Phlorotannins are the dominant phenolic class in brown algae and major contributors to their antioxidant and health-related properties. As phloroglucinol polymers, they act as effective reducing agents and radical scavengers, with studies reporting positive associations between phlorotannin content and antioxidant outcomes, and they are also linked to anti-inflammatory, antidiabetic, and photoprotective activities relevant to oxidative-stress-related chronic diseases [30]. Beyond phenolics, brown algae supply health-relevant proteins, dietary fibre, essential minerals, and carotenoid pigments that synergistically enhance antioxidant potential. For example, *Dictyota* species show high levels of calcium, magnesium, iron, and fucoxanthin alongside substantial phenolic contents and strong antioxidant assay responses, indicating that brown algae can help address both micronutrient gaps and oxidative stress relevant to chronic non-communicable diseases [31].

The relationship between total phenolic content and antioxidant activity in brown-algae extracts is not always proportional, indicating that other constituents and matrix effects substantially influence the overall response. Several studies report samples with moderate phenolic levels but strong radical-scavenging and reducing capacities, likely due to contributions from co-extracted pigments, polysaccharides, minerals, and their synergistic interactions [32]. Furthermore, the use of nonspecific colorimetric assays such as Folin-Ciocalteu and the presence of interfering substances in crude extracts can partially decouple measured total phenols from the true antioxidant performance, complicating direct comparisons across studies and species [33].

Beyond their antioxidant role, brown-algae bioactives are increasingly associated with a range of health-related effects that are relevant for the prevention of chronic, oxidative-stress-driven diseases [34]. Phenolic compounds, phlorotannins, and sulfated polysaccharides from *Phaeophyceae* have been reported to modulate inflammatory mediators, glucose and lipid metabolism, and cellular defense pathways, thereby supporting their potential use in formulations targeting cardiometabolic and other degenerative conditions [35]. At the same time, review articles emphasize that realizing this potential in food applications requires not only efficient and preferably green extraction procedures but also careful consideration of bioaccessibility, stability, and safety of the resulting algae-derived ingredients [36].

In vivo and clinical investigations provide additional support for the antioxidant and health-related potential of brown-algae bioactives in more physiologically relevant settings [37]. Animal studies with brown-algae extracts or isolated phlorotannins improve oxidative, lipid, glucose, and inflammatory markers in metabolic-syndrome and obesity models. Small human trials with seaweed-enriched products also show favourable effects on postprandial glycaemia, blood lipids, and oxidative-stress markers, supporting cardiometabolic potential [38].

However, the health-promoting effects observed *in vitro* and in experimental models cannot be extrapolated uncritically to real-world food applications without addressing issues of bioaccessibility and bioavailability [39]. To bridge this gap, recent research has explored formulation strategies such as encapsulation, emulsification, and incorporation into tailored food matrices to protect sensitive compounds, improve gastrointestinal stability, and achieve more consistent physiological responses in consumers [40]. Beyond systemic antioxidant effects, marine algal extracts and sulfated polysaccharides show promising protective and therapeutic actions in inflammatory bowel disease models, supporting a potential role for algae-derived ingredients in maintaining intestinal barrier function and modulating gut inflammation [41].

D. Technological and Nutritional Considerations for Food Applications

The successful incorporation of brown-algae extracts into foods depends not only on their phenolic content but also on the technological stability of these compounds during processing and storage [42]. Another key aspect is the gastrointestinal fate, bioaccessibility, and bioavailability of marine phenolics and phlorotannins once they are incorporated into foods [13]. *In vitro* digestion and human studies indicate that a substantial fraction of brown-algae phenolics may be bound to the cell wall matrix or form complexes with polysaccharides and proteins, which can limit their release in the upper gut but favour their transformation and utilization by the colonic microbiota [43]. As a result, the *in vivo* antioxidant and health effects may depend more on metabolite profiles and microbiota interactions than on the intact compounds quantified in extracts [31]. Strategies such as partial refining of extracts, encapsulation, or using seaweed ingredients in product categories where marine notes are acceptable have been proposed to overcome these constraints while still delivering meaningful levels of bioactives [17].

Consumer studies also highlight that clear communication of health benefits and sustainability aspects can improve acceptance of seaweed-enriched formulations. Formulation and delivery-system design are emerging as key tools to manage the stability and sensory impact of brown-algae ingredients in complex food matrices. Emulsion-, gel-, and polysaccharide-based systems can improve physical stability, oxidative protection, controlled release, and intestinal solubilization of polyphenols, suggesting similar strategies could enhance the bioavailability and *in vivo* efficacy of phenolic-rich marine-algae extracts in functional foods.

E. Implications, Limitations, and Research Gaps

The technological sensitivity of brown-algae phenolics to processing and storage means that product development must integrate extraction, stabilization, and formulation, not treat extracts as simple additives. Their combined phenolics, minerals, polysaccharides, and fibres make brown-algae ingredients promising for multifunctional foods targeting oxidative stress, mineral deficiencies, and gut health when carefully dosed.

Current evidence is constrained by reliance on in vitro antioxidant assays, heterogeneous extraction and quantification methods, and few long-term human studies, making physiologically relevant doses for real foods hard to define. Safety issues involving iodine and sodium excess, potential heavy-metal accumulation, and strong marine sensory notes further limit feasible inclusion levels and product types.

Key gaps include standardized methods to characterize phlorotannin profiles and stability in complex food matrices, and harmonized bioaccessibility and bioavailability studies that link processing conditions to in vivo metabolite formation. Further research is also needed on consumer perception, regulatory limits, and scalable green-extraction and encapsulation technologies to support routine use of brown-algae phenolics in mainstream functional foods.

IV. Conclusion

Marine and freshwater algae provide diverse phenolic-rich biomasses and co-extracted bioactives with clear potential for functional food applications. Brown seaweeds supply phlorotannin-rich extracts with strong antioxidant and health-related activities, while green, red, and freshwater taxa add complementary phenolics, nutrients, and polysaccharides that may act synergistically. Conventional hydro-organic extractions remain common but are time- and solvent-intensive, whereas green methods such as ultrasound-assisted and subcritical-water extraction can improve efficiency and sustainability. However, heterogeneous methods and limited *in vivo* and human data make physiologically relevant doses difficult to define, and factors such as matrix interactions, bioaccessibility, sensory impact, and safety constraints mean that brown-algae phenolics must be incorporated through carefully designed extraction, stabilization, and delivery systems rather than used as simple additives. Priorities for future research include standardized phlorotannin characterization, harmonized digestion and bioavailability models, and scalable green-extraction and encapsulation technologies to enable safe, effective, clean-label use of algal phenolic ingredients in foods.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Reza Saputra conducted the research; Endang Prangdimurti and Nurheni Sri Palupi analyzed the data; Reza Saputra wrote the paper; Endang Prangdimurti and Nurheni Sri Palupi provided supervision and reviewed the manuscript; all authors had approved the final version.

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REFERENCES

[1] D. Skroza, I. G. Mekinić, F. Burčul, and V. Šimat *et al.*, "Phenolic content of brown algae (Phaeophyceae) species: A review of extraction methods and biological activities," *J. Food Process Eng.*, vol. 42, no. 6, e13193, 2019. doi: 10.1111/jfpe.13193

[2] P. Chellamanimegalai *et al.*, "Unveiling the nutritional and antioxidant properties of brown algae resources (Dictyota J. V. Lamouroux)," *Heliyon*, vol. 11, no. 1, e40693, 2025. doi: 10.1016/j.heliyon.2024.e40693

[3] N. Astuti, H. Hardinsyah, S. Radu *et al.*, "Functional food candidate from Indonesian green algae Caulerpa racemosa (Försskal) J. Agardh by two extraction methods: Metabolite profile, antioxidant activity, and cytotoxic properties," *J. Agric. Food Res.*, vol. 18, 101513, 2024. doi: 10.1016/j.jafr.2024.101513

[4] L. E. Stuthmann, B. B. da Costa, A. J. Cordes *et al.*, "Mono-trophic seaweed polyculture of sea grapes (Caulerpa lentillifera) and Kappaphycus alvarezii: A case study from Van Phong Bay, Viet Nam," *Aquac. Rep.*, vol. 45, 103224, 2025. doi: 10.1016/j.aqrep.2025.103224

[5] F. Nurkolis *et al.*, "Ulvophyte green algae Caulerpa lentillifera: Metabolites, antioxidant, anti-obesity, anti-diabetic and health-promoting effects," *J. Funct. Foods*, vol. 105, 105571, 2023. doi: 10.1016/j.jff.2023.105571

[6] J. Venkatesan, S. K. Kim, and M. S. Shim, "Antimicrobial, antioxidant, and anticancer activities of biosynthesized silver nanoparticles using marine algae Ecklonia cava," *Nanomaterials*, vol. 6, no. 12, 235, 2016. doi: 10.3390/nano6120235

[7] T. Gunathilake, T. Akanbi, B. Wang, and C. Barrow, "Antioxidant benefits of Ecklonia radiata algae phenolic extracts in food grade omega-3 delivery systems," *Future Foods*, vol. 10, no. 1, 100406, 2024. doi: 10.1016/j.fufo.2024.100406

[8] A. Carreira-Casais, P. Otero, P. Garcia-Perez *et al.*, "Benefits and drawbacks of ultrasound-assisted extraction for the recovery of bioactive compounds from marine algae," *Int. J. Environ. Res. Public Health*, vol. 18, no. 17, 9153, 2021. doi: 10.3390/ijerph18179153

[9] Y. Zhang, K. Hawboldt, S. MacQuarrie, and R. Thomas, "Alkaline subcritical water extraction of bioactive compounds and antioxidants from beach-cast brown algae Ascophyllum Nodosum," *Sep. Purif. Technol.*, vol. 346, 127112, 2024. doi: 10.1016/j.seppur.2024.127112

[10] N. Ammari *et al.*, "Sustainable and novel approaches for bioactive compound extraction: Development of hydrodynamic cavitation and coupled machine learning-spline techniques for Ascophyllum nodosum and Fucus vesiculosus," *Food Chem.*, vol. 495, 153526, 2024. doi: 10.1016/j.foodchem.2025.146210

[11] Z. J. Lee, C. Xie, K. Ng, and H. A. R. Suleria, "Study of phenolic-polysaccharide interactions in brown seaweed," *Food Chem.*, vol. 477, 143494, 2025. doi: 10.1016/j.foodchem.2025.143494

[12] S.-Y. Xu, X. Huang, and K.-L. Cheong, "Recent advances in marine algae polysaccharides: Isolation, structure, and activities," *Mar. Drugs*, vol. 15, no. 12, 388, 2017. doi: 10.3390/md15120388

[13] Y. Touhamia, N. Kharrat, A. Aamiri, M. Patel, M. Adnan, N.-E. Rezzoum, L. Pereira, N. Allouche, H. B. Salah, and T. O. B. Lahcen, "In vitro and in silico assessment of antioxidant potential of crude sulfated polysaccharide and phenolic extracts from Gracilaria gracilis macroalgae harvested from Atlantic and Mediterranean coasts: A comparative study," *Algal Research*, vol. 91, 104229, 2025. doi: 10.1016/j.algal.2025.104229

[14] S. Chadorshabi, M. Mohammadi, E. Shamloo, and M. Mahmoudzadeh, "Marine algae-derived bioactives: A sustainable resource for the food and agriculture industries," *Food Front.*, vol. 6, no. 6, pp. 2514–2541, 2025. doi: 10.1016/fft2.70082

[15] J. Mildenberger, J. K. Stangeland, and C. Rebours, "Antioxidative activities and phenolic compounds in Saccharina latissima—A review," *Aquaculture*, vol. 546, 737386, 2022. doi: 10.1016/j.aquaculture.2021.737386

[16] A. Hossain, M. Yasir, Y. Guo, A. Singh *et al.*, "First comprehensive phenolic profiling and antioxidant assessment of red seaweed (Mazzaella japonica) using cold plasma-treated water," *Food Chem.*, vol. 496, no. 1, 146582, 2025. doi: 10.1016/j.foodchem.2025.146582

[17] R. Ullah *et al.*, "Nutritional composition, phenolic contents and antioxidant potential of red seaweed (Gracilariopsis longissima) from the coast of Karachi, Pakistan," *Heliyon*, vol. 10, no. 10, e31002, 2024. doi: 10.1016/j.heliyon.2024.e31002

[18] S. Dhanasundaram, P. Perumal, P. Santhanam, and A. Annamalai, "Brown algae Sargassum wightii derived bioactive compound as potential anti-cancerous agent and molecular docking insights on Hep-2, THP-1 and Cervical cancer cell line," *Results Chem.*, vol. 16, no. 8, 102330, 2025. doi: 10.1016/j.rechem.2025.102330

[19] M. el Mellouki, S. Ait Benichou, N. El Hamdani, and M. Cherki, "Chemical and biological properties of green freshwater alga Ulva intestinalis collected from Casablanca, Morocco," *Egypt. J. Aquat. Res.*, vol. 51, no. 1, 2025. doi: 10.1016/j.ejar.2024.12.006

[20] R. Salih, K. Bajou, B. Shaker, and A. Elgamouz, "Antitumor effect of algae silver nanoparticles on human triple negative breast cancer cells," *Biomed. Pharmacother.*, vol. 168, 115532, 2023. doi: 10.1016/j.biopha.2023.115532

[21] R. Peñalver, J. M. Lorenzo, and G. Nieto, "Bioaccessibility, digestibility and nutritional properties of algae and Cyanophyceae as basis of their potential as functional food ingredients," *Appl. Food Res.*, vol. 4, no. 1, 100404, 2024. doi: 10.1016/j.afres.2024.100404

[22] R. Martínez-Leyva and M. G. Tuohy, "Rapid and cost-efficient microplate assay for total phenolics in beverages and food extracts," *Food Chem. Mol. Sci.*, vol. 6, 100171, 2023. doi: 10.1016/j.fochms.2023.100171

[23] T. Wassie, K. Niu, C. Xie, H. Wang, and W. Xin, "Extraction techniques, biological activities and health benefits of marine algae Enteromorpha prolifera polysaccharide," *Front. Nutr.*, vol. 8, 747928, 2021. doi: 10.3389/fnut.2021.747928

[24] K. Area, K. Kesari, and M. K. Loelhöffel, "Towards optimizing the conventional and ultrasonic-assisted extraction of sulfated polysaccharides from marine algae," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 464, 012007, 2019. doi: 10.1088/1757-899X/464/1/012007

[25] L. Mollo *et al.*, "Screening for tolerance to natural phenols of different algal species: Toward the phycoremediation of olive mill wastewater," *Environ. Sci. Pollut. Res.*, vol. 30, pp. 105809–105820, 2023. doi: 10.1007/s11356-023-29649-1

[26] S. H. Haq, G. Al-Ruwaished, M. A. Al-Mutlaq *et al.*, "Antioxidant, anticancer activity and phytochemical analysis of green algae, Chaetomorpha collected from the Arabian Gulf," *Sci. Rep.*, vol. 9, 18906, 2019. doi: 10.1038/s41598-019-55309-1

[27] A. K. Al Hajri, M. A. Albalawi, I. Alsharif, and B. Jamoussi, "Marine algae extract (Grateloupia sparsa) for the green synthesis of Co_3O_4 NPs: Antioxidant, antibacterial, anticancer, and hemolytic activities," *Adsorpt. Sci. Technol.*, vol. 2022, 3977935, 2022. doi: 10.1155/2022/3977935

[28] G. Sanger, B. E. Kaseger, L. K. Rarung, and L. J. Damongilala, "Chemical constituents and cytotoxicity of the marine green algae Caulerpa racemosa," *J. Agric. Food Res.*, vol. 12, 100621, 2023. doi: 10.1016/j.jafr.2023.100621

[29] Y. Miwa, M. G. G. Awanthi, K. Soga, A. Tanaka, M. Ito, Y. Numata, Y. Sato, and T. Konishi, "The cell wall characterization of brown alga Cladosiphon okamuranus during growth," *Preprints*, 2023081200, 2023. doi: 10.20944/preprints202308.1200.v1

[30] M. Z. Khan, A. I. Mohamed, and M. S. Islam, "The antioxidant, anti-obesogenic, and anti-diabetic potential of selected South African marine algal species," *Front. Pharmacol.*, vol. 15, 1381381, 2024. doi: 10.3389/fphar.2024.1381381

[31] L. Belyagoubi, N. Belyagoubi-Benhammou, and N. Mokhtari-Soulimane, "Biological activity of the freshwater alga Spirogyra sp. from the Algerian desert," *Algal Res.*, vol. 91, 104292, 2025. doi: 10.1016/j.algal.2025.104292

[32] T. T. Phat, T. V. Hoang, T. T. T. Nguyen, H. N. Bao, T. P. Nguyen, and H. T. Nhan, "Enhancing phenolic and flavonoid recovery from Vietnamese balm using green solvent-based ultrasonic-enzymatic-assisted extraction," *Ultrason. Sonochem.*, vol. 121, 107546, 2025. doi: 10.1016/j.ultsonch.2025.107546

[33] D. Granato, J. S. Santos, L. G. Maciel, and D. S. Nunes, "Chemical perspective and criticism on selected analytical methods used to estimate the total content of phenolic compounds in food matrices," *TrAC Trends Anal. Chem.*, vol. 80, pp. 206–221, 2016. doi: 10.1016/j.trac.2016.03.010

[34] S. M. Yacoob, V. Anuradha, R. Abishek, and Y. Nagarajan, "In vitro anticancer activity of green synthesis ruthenium nanoparticle from Dictyota dichotoma marine algae," *NanoWorld Journal*, vol. 3, no. 4, pp. 66–71, 2017. doi: 10.17756/nwj.2017-049

[35] M. C. Barbalace, M. Malaguti, L. Giusti, A. Lucacchini, S. Hrelia, and C. Angeloni, "Anti-inflammatory activities of marine algae in neurodegenerative diseases," *Int. J. Mol. Sci.*, vol. 20, no. 12, 3061, 2019. doi: 10.3390/ijms20123061

[36] P. Deepak, B. Balamuralikrishnan, A. Atef, B. Khalid, and V. Anand, "Phenolic compound derived from Enteromorpha intestinalis and their bioactivity against bacterial pathogens," *J. King Saud Univ. Sci.*, vol. 36, no. 6, 103342, 2024. doi: 10.1016/j.jksus.2024.103342

[37] S. T. Im, W. C. Kim, Y. S. Lee, and J. Y. Kim, "Phenolic-enriched Rosa rugosa extract ameliorates obesity-associated metabolic disorders and regulates gut microbiota in high-fat diet-fed mice," *J. Funct. Foods*, vol. 122, 106548, 2024. doi: 10.1016/j.jff.2024.106548

[38] R. Bhuvaneswari, K. R. Raajshree, R. V. Mala, and R. Rajeswari, "Green biosynthesis of silver nanoparticles using marine red algae Acanthophora specifera and its antimicrobial activity," *J. Nanomed. Nanotechnol.*, vol. 7, no. 6, 1000409, 2016. doi: 10.4172/2157-

7439.1000409
[39] J. Alberdi-Cedeño, A. Auñon-Lopez, A. Martinez-Yusta, and M. D. Guillen, "Understanding the bioaccessibility of lipidic compounds and the formation of free oxylipins of encapsulated omega-3-rich marine oils during in vitro digestion," *LWT*, vol. 234, 118574, 2025. doi: 10.1016/j.lwt.2025.118574
[40] J. Kavitha and P. Subramani, "Phytochemical screening, GC-MS analysis and antioxidant activity of marine algae Chlorococcum humicola," *World J. Pharm. Pharm. Sci.*, vol. 5, no. 6, pp. 1154–1167, 2016. doi: 10.20959/wjpps20166-6871
[41] N. N. Besednova *et al.*, "Extracts and marine algae polysaccharides in therapy and prevention of inflammatory diseases of the intestine," *Mar. Drugs*, vol. 18, no. 6, 289, 2020. doi: 10.3390/md18060289
[42] Y. Zhang, K. Hawboldt, and S. MacQuarrie, "Extraction of bioactive compounds from beach-cast brown algae: A review on accelerated solvent extraction and subcritical water extraction," *Sustainability (RSC)*, vol. 1, no. 6, pp. 2069–2091, 2024. doi: 10.1039/D4SU00204K
[43] M. I. Alkhalaf, "Chemical composition, antioxidant, anti-inflammatory and cytotoxic effects of Chondrus crispus species of red algae collected from the Red Sea along the shores of Jeddah city," *J. King Saud Univ. Sci.*, vol. 33, no. 1, 101210, 2021. doi: 10.1016/j.jksus.2020.10.007