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Sustainable Nutrition from the Ocean: Trend of Edible Green Seaweeds in Food and Functional Product Development

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ABSTRACT
Edible green seaweeds (*Chlorophyta*) are increasingly recognized as sustainable resources for advancing human nutrition and driving functional food innovation. Rich in essential nutrients and bioactive compounds, and requiring minimal environmental inputs for cultivation, genera such as *Ulva*, *Caulerpa*, and *Codium* present promising opportunities for resilient food systems. This review analyzes 148 documents indexed in Scopus (1985–2025) on the use of green seaweeds as functional foods. The findings reveal a marked increase in research output after 2016, coinciding with a global shift toward sustainable dietary strategies. Keyword network analysis identified key research themes such as "functional food," "nutrition," "bioactivity," and "antioxidants," with emerging interest in novel extraction technologies. Nutritional assessments show that edible green seaweeds are rich in proteins, carbohydrates, dietary fiber, minerals, and a variety of bioactive compounds—including ulvans, polysaccharides, sterols, carotenoids, and polyphenols. These constituents are linked to antioxidant, anti-inflammatory, antimicrobial, and cardioprotective effects. Application-wise, green seaweeds have been incorporated into functional ingredients, protein supplements, hydrocolloids, fermented foods, fortified snacks, functional beverages, and even sustainable food packaging. Despite their potential, challenges remain in areas such as taste masking, extraction optimization, product stability, and regulatory compliance, which must be addressed to enhance commercial viability. This review underscores the growing significance of edible green seaweeds in future food innovation, particularly within the context of sustainable and health-promoting food products. Their integration into the functional food sector presents substantial opportunities aligned with global efforts to develop more resilient and eco-friendly food systems.

INTRODUCTION

Edible green seaweeds are increasingly recognized as a valuable yet underutilized resource for advancing sustainable nutrition and driving innovation in functional food products. Rich in essential nutrients and bioactive compounds—and requiring minimal environmental inputs for cultivation—these marine macroalgae offer promising solutions to enhance food security and support the development of health-oriented foods. As global efforts intensify to build resilient and eco-friendly food systems, the contribution of edible green seaweeds to sustainable dietary strategies is becoming more significant **(Cavallo *et al.*, 2021; Adeniyi *et al.*, 2024)**.

Belonging to the division *Chlorophyta*, edible green seaweeds are notable for their green pigmentation, attributed to chlorophyll a and b as well as various xanthophylls **(Peng *et al.*, 2015)**. These macroalgae are commonly distributed across intertidal and subtidal coastal zones worldwide **(Thiruchelvi *et al.*, 2018)**. Prominent genera include *Ulva*, *Caulerpa*, and *Enteromorpha*, all of which are gaining attention for their nutritional content and wide-ranging applications in human diets. *Ulva*, commonly referred to as sea lettuce, is particularly valued for its rapid growth and its capacity to form extensive blooms known as "green tides" **(Dominguez & Loret, 2019; Wichard, 2023)**. Beyond its ecological impact, *Ulva* is used in bioremediation and is a known source of bioactive compounds **(Hardegen *et al.*, 2023)**. Likewise, species of *Caulerpa*, such as *Caulerpa taxifolia*, are recognized for their invasive behavior and distinct cellular structures **(Thygesen *et al.*, 2021)**. *Enteromorpha*, frequently found in nutrient-rich environments, is closely related to *Ulva*, with many of its species having been reclassified under the same genus **(Dominguez & Loret, 2019)**.

Several edible green seaweeds stand out for their nutritional attributes. *Caulerpa lentillifera*—commonly known as sea grapes or green caviar—is rich in proteins, carbohydrates, and dietary fiber, and is prized for its unique texture and health benefits **(Stuthmann *et al.*, 2023a)**. *Ulva* species provide a rich supply of essential amino acids, minerals, and fiber, along with diverse bioactive compounds with potential human health benefits **(Sanjeewa *et al.*, 2024)**. *Codium* species are also noteworthy for their high content of proteins, carbohydrates, and essential fatty acids, including distinctive lipid profiles **(Arakaki *et al.*, 2023a)**.

Amid rising concerns over global food insecurity and growing consumer demand for functional foods, edible green seaweeds have garnered increasing interest as sustainable marine resources. Their diverse bioactivities have enabled their integration into a wide array of functional food applications. These seaweeds serve as natural gelling, thickening, and emulsifying agents, enhancing both the nutritional value and technological functionality of food products **(Lomartire *et al.*, 2022; Ali *et al.*, 2024a)**. As a result, they are considered vital contributors to addressing food security and advancing the transition toward more sustainable, resilient, and health-promoting food systems **(Kumar *et al.*, 2023)**.

This review provides a comprehensive overview of edible green seaweeds, with a focus on publication trends, nutritional properties, and their applications in food and functional product development.

MATERIALS AND METHODS

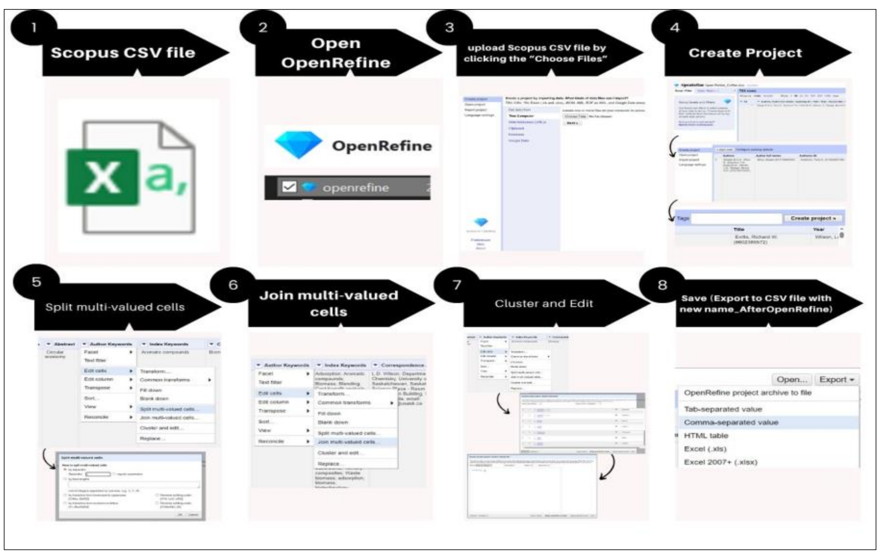
The study employed the Scopus database using the search term "Green Seaweed as a Functional Food", yielding a total of 148 documents spanning the years 1985 to 2025. This collection included 82 research articles, 46 review papers, and 20 book chapters. The search was conducted on January 5, 2025, and the resulting data were exported in MS Excel CSV format.

Data cleaning and preprocessing were performed using OpenRefine, which facilitated the removal of duplicate entries and ensured data consistency. This process involved refining both Author Keywords and Index Keywords through techniques such as splitting multi-valued cells, clustering similar terms, and merging related entries. The cleaned dataset was then saved in an updated Excel CSV format for further analysis.

Tableau 2022.2 was used to visualize trends in publication output over time, while VOSviewer was employed to generate a keyword co-occurrence network, with thematic clusters represented in different colors (Fig. 1).

Additionally, Scopus was utilized to identify literature focusing on three key areas: the nutritional value of green seaweeds, the bioactive compounds they contain, and their applications in food and functional food development between 1985 and 2025.

a)



b)

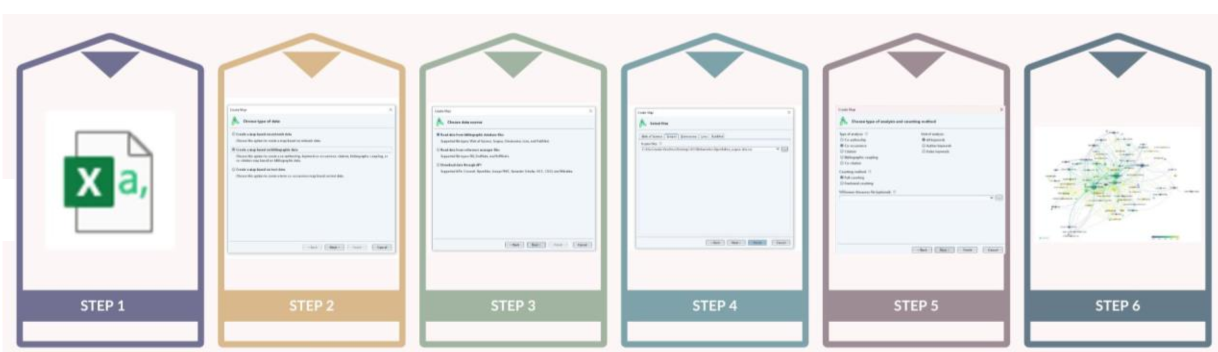


Fig. 1. Workflow of data processing using a) OpenRefine; b) VOSviewer

RESULTS AND DISCUSSION

1. Trend publication of edible green seaweed as a functional food

The publication output has shown an increasing trend since 2016, following a period of relatively low and fluctuating output between 2009 and 2015. Most publications were research articles, while book chapters and review papers comprised a smaller portion. The highest number of publications was recorded in 2024, totaling 24 documents, with the majority being research articles. An upward trend was seen in the number of documents published each year (Fig. 2).

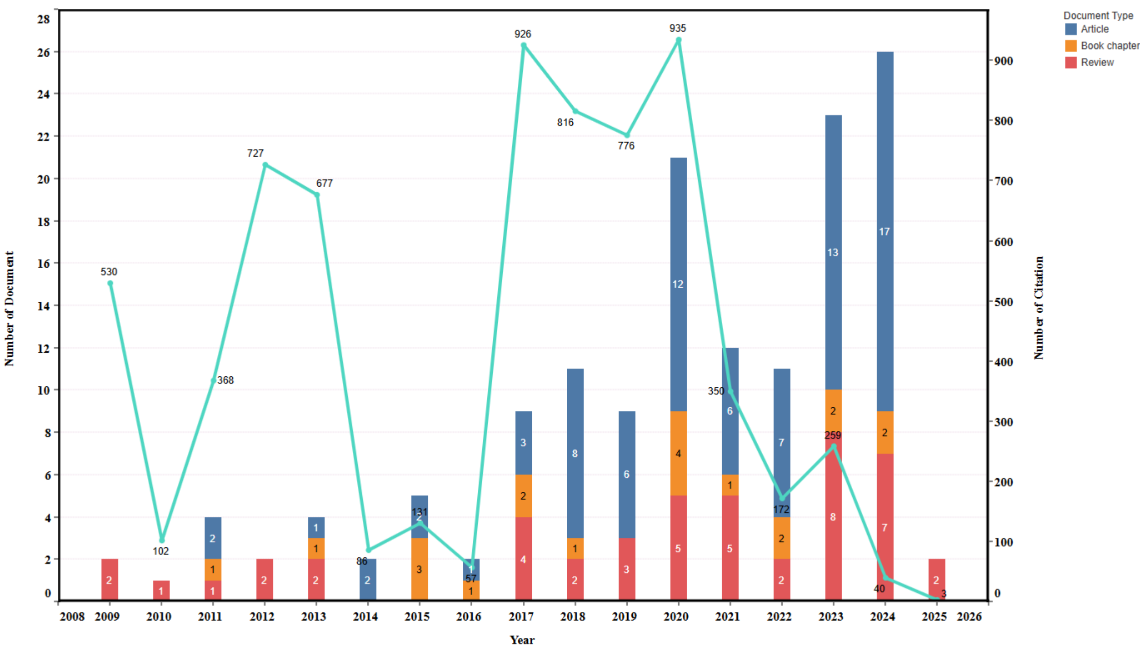


Fig. 2. Trends in the count of publications from 2009 to 2025 related to green seaweed as a functional food. The horizontal coordinate represents the year. The left vertical coordinate represents the number of documents, and the right vertical coordinate represents the number of citations. The number reported in 2025 is for an incomplete year

Citation trends exhibited significant variation over the years. The highest citation counts were observed in 2016, with 926 citations, and in 2018, with 935 citations. These peaks reflect the influence of publications from earlier years. Following 2020, citation counts generally declined even though the number of publications increased, indicating a potential citation lag for newer works. Additionally, 2011 and 2012 experienced notable citation peaks of 727 and 697 citations, respectively, despite the relatively modest number of publications during those years.

The analysis of publication and citation trends from 2009 to 2025 reveals several important patterns. Early years (2009–2015) showed relatively low publication outputs with modest citation numbers, indicating limited research activity or lower visibility during that period. A significant shift occurred beginning in 2016, marked by a steady increase in the number of publications, predominantly in the form of research articles. This trend suggests an intensification of research efforts and a growing emphasis on disseminating findings through peer-reviewed articles. According to **Boudreaux *et al.* (2019)**, citation counts are a common metric for evaluating research impact.

Interestingly, citation counts peaked sharply in 2016 and 2018, despite relatively fewer publications in preceding years. These peaks may be attributed to the publication of highly cited works during that time, highlighting the potential influence of a few impactful papers on overall citation metrics. After 2020, although the number of publications continued to rise, reaching its highest point in 2024, the corresponding citation counts declined. This pattern likely reflects the common citation lag phenomenon, where newer publications require time to accumulate citations **(Donner, 2018; Ma *et al.*, 2019)**. Top publications were cited >200 times, as presented in Table (1).

Table 1. Information on the most cited articles (> 200 cited) in research into seaweed as a functional food

Title	Document Type	Source Title	Year	Cited by	Ref
Seaweeds: A sustainable functional food for complementary and alternative therapy	Review	Trends in Food Science and Technology	2012	435	(Mohamed *et al.*, 2012)
In vitro antioxidant properties of crude extracts and compounds from brown algae	Review	Food Chemistry	2013	369	(Balboa *et al.*, 2013)
Recent advances in marine algae polysaccharides: Isolation, structure, and activities	Review	Marine Drugs	2017	325	(Xu *et al.*, 2017)
Recent developments in the application of seaweeds or seaweed extracts as a means for enhancing the safety and quality attributes of foods	Review	Innovative Food Science and Emerging Technologies	2011	299	(Gupta & Abu-Ghannam, 2011)
Characteristics and nutritional and cardiovascular-health properties of seaweeds	Review	Journal of Medicinal Food	2009	297	(Bocanegra *et al.*, 2009)
Enzyme-assistant extraction (EAE) of bioactive components: A useful approach for recovery of industrially important metabolites from seaweeds: A review	Review	Fitoterapia	2012	292	(Wijesinghe & Jeon, 2012)
Functional properties of carotenoids originating from algae	Review	Journal of the Science	2013	280	(Christaki *et al.*, 2013)

		of Food and Agriculture			
Seaweeds as a functional ingredient for a healthy diet	Review	Marine Drugs	2020	260	(Peñalver *et al.*, 2020)
The okinawan diet: Health implications of a low-calorie, nutrient-dense, antioxidant-rich dietary pattern low in glycemic load	Review	Journal of the American College of Nutrition	2009	233	(Willcox *et al.*, 2009)

Moreover, the relatively consistent presence of review papers and book chapters suggests diversification in publication strategies, aiming not only for original research dissemination but also for scholarly contributions in synthesized knowledge and academic compilations.

2. Keyword co-occurrence analysis

The keyword co-occurrence analysis (Fig. 3) identified several dominant research themes within the dataset. The most prominent keywords, based on node size and centrality, were "seaweed," "functional food," "macroalgae," and "antioxidant." These core terms were closely linked to concepts such as "nutrition," "health benefits," "bioactivity," and "green seaweed," suggesting a strong research emphasis on the nutritional and functional potential of marine macroalgae.

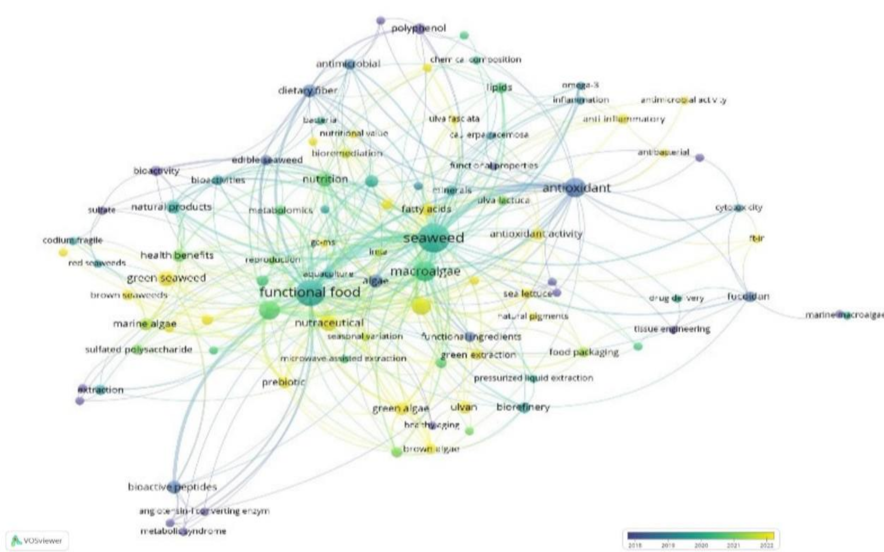


Fig. 3. Network visualization of keywords. The larger the bubble, the more keywords are utilized by authors

The temporal distribution of keywords, visualized using a color gradient (blue-green for earlier studies and yellow for more recent ones), reflects an evolving research focus over time. Between 2018 and 2019, studies primarily emphasized the nutritional properties, antioxidant activities, and general health benefits of green seaweeds. In contrast, the period from 2021 to 2022 saw the emergence of novel keywords such as "microwave-assisted extraction," "biorefinery," and "pressurized liquid extraction," indicating a shift toward advanced technological approaches aimed at optimizing the extraction and application of bioactive compounds.

The recurring presence of keywords related to "nutrition" and "health benefits" highlights the rich nutritional profile of edible green seaweeds (Table 2). Species such as *Caulerpa lentillifera*, *Ulva* spp., *Codium* spp., and *Cladophora* spp. are well-documented for their high contents of protein, carbohydrates, dietary fiber, and essential minerals, while maintaining a low-fat profile. For example, *Caulerpa lentillifera* contains 14.4% protein and 32.95% carbohydrates, along with notable amounts of dietary fiber and ash **(Stuthmann *et al.,* 2023b)**. *Ulva* species are particularly valued for their high protein and fiber levels, whereas *Codium* species exhibit a relatively higher fat content. These characteristics position green seaweeds as promising nutritional ingredients, particularly in response to the increasing demand for plant-based proteins and dietary fibers. This growing interest reinforces their potential as sustainable, nutrient-dense alternatives in the development of functional food products.

The keyword network also emphasized "bioactivity" and "antioxidant" as core themes (Table 3), reflecting the wide array of bioactive compounds present in green seaweeds. These include sulfated polysaccharides (e.g., *ulvans*), phenolic compounds, peptides, sterols, chlorophyll, carotenoids, and dietary fiber. Collectively, these compounds contribute to antioxidant, anti-inflammatory, antihypertensive, and gut health–enhancing effects. As such, green seaweeds are increasingly regarded as valuable sources of health-promoting compounds with potential applications in functional foods, nutraceuticals, and pharmaceuticals **(Qin, 2020; Putra *et al.,* 2024)**.

Overall, the keyword network analysis demonstrates a progression in the research landscape—from foundational studies on nutrient composition to a more integrated focus combining nutritional profiling, bioactivity exploration, and innovative extraction technologies. The strong association among the terms "green seaweed," "health benefits," and "functional food" underscores the central importance of their nutritional and biofunctional roles in shaping the future of sustainable food innovation.

Table 2. Nutritional composition of selected edible green seaweeds

Seaweed Type	Protein (%)	Carbohydrates (%)	Lipid (%)	Dietary Fiber (%)	Ash (%)	Minerals	Ref.
Caulerpa lentillifera	14.4; 12.49	32.95	0.85	High	41.85; 24.21	Iodine, Phosphorus, Calcium, Magnesium, Copper	(Ratana-arporn & Chirapart, 2006); (Stuthmann *et al.*, 2023b)
Caulerpa racemosa	8.8-19.9; 20.27 ± 0.14	33.42 ± 1.34	4.20 ± 0.32		28.25 ± 0.27	Na, K, Mg, Ca, P, Fe, Mn, Zn, Cu	(Aroyehun *et al.*, 2020; Magdugo *et al.*, 2020)
Ulva lacinulata	21.06				17.58	Iodine, Potassium, Manganese, Ferrous	(Ratana-arporn & Chirapart, 2006)
Ulva lactuca	High; 12.06	Moderate; 66.1	Low	High	Moderate		(Arakaki *et al.*, 2023b; Asanka Sanjeewa *et al.*, 2024)
Ulva linza	12.89						(Mani *et al.*, 2024b)
Ulva sp.	9.24	49.09	0.38		31.4	Sodium, Magnesium	(Jatmiko *et al.*, 2019)
Halimeda gracilis					35.12	Calcium, Magnesium, Phosphorus	(Mani *et al.*, 2024b)
Codium intricatum		32.16			37.16	Natrium, K, Ca, Mg, Fe, Mn, Pb, Zn, Cu, Cd, Cr	(Arguelles, 2020)
Codium species	Moderate	Moderate	High	Moderate	Moderate		(Arakaki *et al.*, 2023b)
Cladophora species	Moderate	High	Low	High	Moderate		(Kumar *et al.*, 2024)

Table 3. Bioactive compounds in green seaweeds and health benefits

Compound	Source (Species)	Functional Properties	Health Benefits	References
Ulvans	*Ulva* spp. (e.g. *Ulva lactuca*,	Antioxidant, Anticoagulant,	Enhances cell proliferation and migration,	(Rupérez *et al.*, 2013; Udayangani *et*

	Ulva australis, *Ulva rigida*	Immunomodulatory, Antitumor	Reduces inflammation Improves phagocytosis, Potential in wound healing and tissue regeneration	*al.*, 2020; Kidgell *et al.*, 2021; Premarathna *et al.*, 2024)
Polysaccharides	*Caulerpa* spp.	Antioxidant, Antimicrobial, Prebiotic	Reduces oxidative stress, Promotes gut health, Protects against infections	(Palaniyappan *et al.*, 2023; Mani *et al.*, 2024a)
Sterols (e.g. fucosterol)	*Ulva expansa*, *Caulerpa* spp.	Cholesterol-lowering properties, antioxidant activity	Reduces cholesterol levels, supports cardiovascular health, and provides antioxidant benefits	(Osuna-Ruiz *et al.*, 2019; Darmawan *et al.*, 2020)
Chlorophyll	*Caulerpa* spp. *Ulva* spp.	Antioxidant, anti-inflammatory, and detoxifying properties	Enhances detoxification, reduces inflammation, and provides antioxidant protection	(Darmawan *et al.*, 2020; Mani *et al.*, 2024b)
Carotenoids (β-carotene, lutein)	*Caulerpa* spp. *Ulva* spp.	Antioxidant properties, supports eye health	Protects against oxidative stress, supports eye health, and reduces the risk of age-related macular degeneration	(Osuna-Ruiz *et al.*, 2019; Darmawan *et al.*, 2020)
Polyphenols	*Caulerpa* spp. *Ulva* spp. *Codium* spp.	Antioxidant, anti-inflammatory, and antimicrobial properties	Reduces oxidative stress, inflammation, and microbial infections	(Tanna *et al.*, 2019; Zhong *et al.*, 2020; Cadar *et al.*, 2023)

Amino Acids	*Caulerpa* spp. *Ulva* spp.	Essential for protein synthesis, supports muscle health	Supports muscle growth and repair, provides essential nutrients for overall health	(Tanna *et al.*, 2019; Darmawan *et al.*, 2020)
Fatty Acids (PUFAs)	*Caulerpa* spp. *Ulva* spp.	Anti-inflammatory, supports cardiovascular health	Reduces inflammation, supports heart health, and improves lipid profiles	(Darmawan *et al.*, 2020; Osuna-Ruiz *et al.*, 2019)
Sulfated Arabinogalactans	*Codium* spp.	Anticoagulant, Antiviral, Antioxidant, Antitumor, Immunomodulatory	Reduces blood clotting, Enhances immune response, Protects against viral infections	(Wang *et al.*, 2014b)
Vitamins (e.g. Vitamin C, E)	*Caulerpa* spp. *Ulva* spp.	Antioxidant properties, supports immune function	Enhances immune function, provides antioxidant protection, and supports overall health	(Ferraces-Casais *et al.*, 2012; Darmawan *et al.*, 2020)

3. Applications of seaweeds in the development of functional products

Consistent with the keyword clusters surrounding "functional food" and "macroalgae," the application of green seaweeds in the food industry has diversified significantly. As shown in Table (4), green seaweeds are incorporated into functional ingredients, hydrocolloids, protein supplements, fermented products, fortified snacks, cosmeceuticals, and functional beverages.

Green seaweeds have shown remarkable versatility in today's food industry, appearing in a wide range of products such as seaweed smoothies, protein powders, plant-based dairy alternatives, seaweed crackers, and marine collagen drinks. Their growing popularity is largely due to their ability to serve as functional ingredients that offer health benefits beyond basic nutrition, including promoting gut health, delivering antioxidants, and providing antimicrobial effects. In addition to their functional properties, seaweeds also act as natural food additives and preservatives, helping to enhance both the nutritional value and shelf life of various products by serving as thickeners, gelling agents, and emulsifiers **(Gupta & Abu-Ghannam, 2011; Ali *et al.*, 2024b)**. Building on these advantages, seaweeds are increasingly being incorporated into innovative food products, where they not only boost nutritional content but also improve taste and texture, leading to the development of hybrid or composite health foods featuring seaweed as a key component. However, challenges remain regarding taste masking, extraction efficiency, shelf-life extension, and regulatory compliance **(Perez-Vazquez *et al.*, 2023; Jönsson *et al.*, 2024)**.

Table 4. Applications of seaweeds in food and functional product development

Application Area	Description	Product Examples	Challenges	References
Food Packaging	Seaweed compounds are used in food packaging due to their gelling, thickening, and emulsifying properties. They enhance food durability, nutritional value, and reduce bacterial growth	Fresh produce packaging, Seafood packaging, Bakery packaging, Confectionery packaging	Production scalability, Property improvements, Ensuring biodegradability and environmental friendliness	(Ali *et al.*, 2024a, 2025)
Functional Ingredients	Used as powders or extracts in health foods and beverages to enhance nutritional, textural, and sensory properties.	Smoothies, energy bars, green seaweed capsules	Taste, odor, consumer acceptability, presence of toxins, microplastics, heavy metals, and micropollutants	(A. Kumar *et al.*, 2023; Pasdar *et al.*, 2024)
Hydrocolloids & Texturizers	Used as gelling, thickening, and emulsifying agents in food products.	Agar, carrageenan, alginate-based products.	Stability, bioavailability, and extraction challenges.	(Quitério *et al.*, 2021; Ali *et al.*, 2024a)
Algae-based Protein Supplements	Seaweed proteins and peptides used for their nutritional benefits.	Protein powders, supplements.	Taste, odor, consumer acceptability.	(Ferrara, 2020; A. Kumar *et al.*, 2023)
Fermented and Traditional Foods	Fermentation of seaweed biomass to produce functional foods	Fermented seaweed products,	Underdeveloped fermentation techniques.	(Ferrara, 2020; Monteiro *et al.*, 2021;

	with enhanced prebiotic and probiotic properties.	traditional seaweed dishes.		Reboleira *et al.*, 2021)
Fortified Snacks and Meals	Seaweed powders or extracts added to enhance nutritional content.	Energy bars, fortified meals, snacks.	Taste, odor, consumer acceptability.	(A. Kumar *et al.*, 2023; Pasdar *et al.*, 2024)
Cosmeceuticals and Functional Drinks	Seaweed extracts used for their bioactive compounds in health beverages and skincare products.	Smoothies, energy drinks, skincare products.	Stability, extraction efficiency.	(Qin, 2020; Monteiro *et al.*, 2021)

CONCLUSION

Edible green seaweeds represent a highly promising and sustainable resource for the development of functional foods, contributing significantly to global food security. Their rich nutritional profiles comprising proteins, dietary fibers, essential minerals, and bioactive compounds such as ulvans, polysaccharides, sterols, and carotenoids provide numerous health benefits, including antioxidant, anti-inflammatory, antimicrobial, and cardiovascular protective effects. A bibliometric analysis of publication trends from 1985 to 2025 reveals a marked increase in research output since 2016, underscoring a growing scientific and commercial interest in the potential of green seaweeds. Additionally, keyword co-occurrence analysis indicates a shift in research focus from basic nutritional studies to the implementation of advanced extraction technologies and biorefinery applications, highlighting the increasing sophistication of the field. The application of edible green seaweeds within the food industry has diversified significantly. It now encompasses functional ingredients, protein supplements, fermented foods, fortified snacks, beverages, and sustainable food packaging. These advancements illustrate the versatility of green seaweeds in fostering eco-friendly and health-promoting food systems. Nevertheless, challenges related to taste masking, extraction efficiency, product stability, and regulatory frameworks must be addressed to fully unlock their commercial potential. Edible green seaweeds offer substantial opportunities for innovation in sustainable and functional food products. Future research should prioritize overcoming technological and sensory challenges, optimizing the extraction of bioactive compounds, and ensuring product safety and regulatory compliance. By pursuing these avenues, the integration of green seaweeds into mainstream diets can be accelerated, thereby supporting the transition toward resilient, health-oriented global food systems.

Competing interests

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

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