Food Research 10 (2) : 464 - 473 (April 2026)
Journal homepage: https://www.myfoodresearch.com

FOOD RESEARCH

MINI REVIEW

A perspective on seaweeds as a potential prebiotic source and its food applications

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Article history:
Received: 20 December 2024
Revised: 3 February 2025
Accepted: 10 February 2025
Published: 30 April 2026

Keywords:
Prebiotic,
Seaweed,
Short chain fatty acids,
Sustainable,
Polysaccharide,
Gastrointestinal health

DOI:
https://doi.org/10.26656/fr.2017.10(2).272

Abstract

Prebiotics play a crucial role in enhancing gut health by selectively stimulating beneficial gut microbiota. This review explores the potential of seaweeds as novel prebiotic sources, focusing on their nutritional profile, health benefits, and food applications. Seaweeds, comprising red, green, and brown varieties, are rich in bioactive compounds, including polysaccharides such as alginates, carrageenans, and agar, which exhibit prebiotic properties by resisting digestion and fermenting in the colon. The fermentation process promotes the production of short-chain fatty acids, contributing to gut health and systemic benefits. As sustainable and nutrient-rich food ingredients, seaweeds have been traditionally utilized in various cultures for their culinary and medicinal properties. Recent innovations in the food industry have integrated seaweed-derived prebiotics into functional foods and dietary supplements, responding to the rising consumer demand for natural health-promoting ingredients. Despite their promise, challenges such as variability in composition and potential contaminants necessitate further research. This review aims to provide a comprehensive understanding of seaweed prebiotics, their mode of action, and future directions for enhancing their applications in health and nutrition.

1. Introduction

Prebiotics are non-digestible food components that positively affect the host by selectively stimulating the growth and activity of specific beneficial microorganisms in the gut, particularly bifidobacteria and lactobacilli. Unlike probiotics, which are live bacteria introduced into the gut, prebiotics act as a food source for these good bacteria, helping them to thrive and maintain a healthy balance in the gut microbiome (Davani-Davari *et al*., 2019). The most common types of prebiotics include certain fibers and oligosaccharides, such as inulin, fructooligosaccharides, and galactooligosaccharides. These compounds resist digestion in the upper gastrointestinal tract and reach the colon intact, where they are fermented by the gut microbiota, leading to the production of short-chain fatty acids (SCFAs) such as butyrate, propionate, and acetate, which have several health-promoting effects (Liu *et al*., 2017).

The role of prebiotics in human health is being increasingly recognized for its potential in the prevention and management of various diseases (Manzoor *et al*., 2022). The production of SCFAs through fermentation not only lowers the pH of the intestinal environment, inhibiting the growth of pathogenic bacteria, but also serves as an energy source for colonocytes, contributing to intestinal integrity (Rini *et al*., 2024). Prebiotics have been associated with improved digestive health, enhanced immune function, and reduced risk of metabolic diseases such as obesity and type 2 diabetes (Manzoor *et al*., 2022). In addition, prebiotics have shown promise in mental health by influencing the gut-brain axis, suggesting their potential role in alleviating symptoms of anxiety and depression (Ansari *et al*., 2023). As research continues to uncover the broad benefits of prebiotics, there is growing interest in identifying and utilizing novel prebiotic sources, such as seaweed, that offer the added benefits of sustainability and nutrient richness.

Seaweeds, a diverse group of marine algae, have been an integral part of traditional diets and cultures around the world for centuries, particularly in coastal regions (Tiitii *et al*., 2022). Algae are classified into ten groups based on their color, which is determined by their

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eISSN: 2550-2166 / © 2026 The Authors.
Published by Rynnye Lyan Resources

pigment composition and structural characteristics. These groups include blue-green (Cyanophita), pyrrophytic (Pyrrophyta), golden (Chrysophyta), diatoms (Bacillariophyta), yellow-green (Xanthophyta), brown (Phaeophyta), red (Rhodophyta), euglenophytic (Euglenophyta), green (Chlorophyta), and charophytic (Charophyta). Each group possesses distinct characteristic polysaccharides (Zaporozhets, 2014). In Asia, especially in countries such as Japan, Korea and China, seaweeds such as nori, kombu and wakame are staple ingredients, valued not only for their nutritional benefits but also for their unique flavors and textures. These seaweeds are commonly used in soups, salads, sushi, and as condiments. In Europe, especially in Ireland and Scotland, seaweeds such as dulse and kelp have been traditionally harvested and used as both food and medicine. Indigenous peoples along the Pacific coast of North America have also long relied on seaweed as a vital food source, rich in essential nutrients such as iodine, vitamins, and minerals (O'Connor, 2017). Beyond their culinary uses, seaweeds have played a role in traditional medicine, where they are believed to have therapeutic properties, including anti-inflammatory and antioxidant effects (Lomartire *et al*., 2021). The cultural significance of seaweed extends to its use in rituals, cosmetics, and even as an agricultural fertilizer (O'Connor, 2017). This deep-rooted history of seaweed use across cultures underscores its enduring value and sets the stage for its modern applications in health and nutrition, particularly as a potential prebiotic source.

The growing interest in natural, sustainable sources of prebiotics is being driven by a convergence of factors, including increasing awareness of gut health, rising demand for functional foods and the global push for environmental sustainability. Consumers are becoming more aware of the long-term impact of their dietary choices, leading to a preference for foods that not only promote personal health but also have a minimal environmental footprint (Nelson *et al*., 2016). This has led to a surge in research and development focused on identifying prebiotic sources that are not only effective but also in line with sustainable practices. Seaweeds, in particular, have received significant attention due to their rich content of prebiotic fibers, such as alginates, carrageenans and agar, coupled with their low environmental impact. Unlike traditional crops, seaweeds do not require fresh water, fertilizers or arable land to grow, making them an attractive, environmentally friendly alternative. This interest is driven by the increasing need to diversify the global food supply and address challenges such as climate change and food security, positioning seaweeds as a promising sustainable source of prebiotics that can contribute to both human health and environmental preservation (Zheng *et al*., 2019; Jayakody *et al*., 2022).

This review aimed to explore the potential of seaweeds as a source of prebiotics and to examine their current and potential applications in the food industry. Seaweeds rich in polysaccharides such as alginate, carrageenan and agar have shown promise in promoting gut health and providing various health benefits. This review aims to provide a comprehensive understanding of how these compounds function as prebiotics, their impact on the gut microbiome, and their incorporation into functional foods and dietary supplements.

2. Seaweeds: composition and nutritional profile

Seaweeds are classified into three main types based on their pigmentation and biochemical composition: red (Rhodophyta), green (Chlorophyta), and brown (Phaeophyta) seaweeds (Lopez-Santamarina *et al*., 2020). Red seaweeds, such as nori (*Porphyra*) and dulse (*Palmaria palmata*), are rich in phycoerythrin, giving them their distinctive color, and are widely used in sushi and other Asian cuisines (Kumar *et al*., 2021). They are commonly found in warm, tropical waters but also thrive in cooler regions. Green seaweeds, like sea lettuce (*Ulva*) and codium, contain chlorophyll, which gives them their bright green hue. They are often found in both marine and freshwater environments and are used in salads, soups, and as garnishes. Brown seaweeds, including kelp (*Laminaria*), wakame (*Undaria pinnatifida*), and kombu, are abundant in fucoxanthin, which imparts a brownish color. These seaweeds are primarily found in colder, nutrient-rich waters of the northern hemisphere and are widely used in broths, soups, and as flavor enhancers in various dishes. Geographically, seaweeds are distributed across the globe, with significant harvesting occurring along the coasts of Japan, Korea, China, Norway, Canada, and the United States. Each region cultivates species suited to its local marine environment, contributing to the global diversity of seaweed species used in food and other applications (Baweja *et al*., 2016).

Seaweeds are renowned for their rich and diverse chemical composition, making them valuable not only as food but also as sources of bioactive compounds. A key component of seaweeds is their polysaccharides, also commonly referred to as dietary fiber, which vary among different types of seaweeds (Peng *et al*., 2015), as shown in Table 1. Alginate, primarily found in brown seaweeds, is a gel-forming polysaccharide used in food and industrial applications for its thickening and stabilizing properties (Rashedy *et al*., 2021). Carrageenan, extracted from red seaweeds, is widely used in the food industry as a gelling agent, especially in dairy and meat products. Agar, another polysaccharide from red seaweeds, is utilized as a vegetarian gelatin substitute and in

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Table 1. Dietary fiber content of seaweeds.

Type of seaweed	Dietary fiber content (% Dry Weight)*	References
Brown seaweeds	35-62	Kraan (2012)
Alaria esculenta	42.86	
Cystoseira abies-marina	56.34	Patarra *et al*. (2011)
Eisenia bicyclis	10-75	
Fucus spiralis	63.88	Patarra *et al*. (2011)
Fucus vesiculosus	45-59	De Jesus Raposo *et al*. (2016; Rupérez and Saura-Calixto (2001)
Himanthalia elongata	32.7-37	De Jesus Raposo *et al*. (2016)
Hizikia fusiforme	62.3	Dawczynski *et al*. (2007)
Laminaria sp.	36	Dawczynski *et al*. (2007)
Laminaria digitata	36-37	De Jesus Raposo *et al*. (2016)
Laminaria/Saccharina japonica	10-41	De Jesus Raposo *et al*. (2016)
Saccharina latissima	30	De Jesus Raposo *et al*. (2016)
Sargassum fusiforme	17-69	De Jesus Raposo *et al*. (2016)
Undaria pinnatifida	16-51	Dawczynski *et al*. (2007)
Red Seaweeds		
Chondrus crispus	10-34	De Jesus Raposo *et al*. (2016)
Gelidium microdon	57.37	Patarra *et al*. (2011)
Gracilaria changii	28.0	Norziah and Ching (2000)
Hypnea charoides	50.3	Wong and Cheung (2000)
Hypnea japonica	53.2	Wong and Cheung (2000)
Osmundea pinnatifida	33.82	Patarra *et al*. (2011)
Palmaria palmate	29-48.6	De Jesus Raposo *et al*. (2016)
Porphyra sp.	35-49	Dawczynski *et al*. (2007; Patarra *et al*. (2011)
Pyropia tenera	12-35	De Jesus Raposo *et al*. (2016)
Porphyra umbilicalis	29-43	De Jesus Raposo *et al*. (2016)
Pyropia yezoensis	30-59	De Jesus Raposo *et al*. (2016)
Porphyridium sp.	35.5-45	Dvir *et al*. (2000)
Pterocladia capillacea	52.08	Patarra *et al*. (2011)
Sphaerococcus coronopifolius	41.25	Patarra *et al*. (2011)
Green seaweeds		
Caulerpa lentillifera	38-59	De Jesus Raposo *et al*. (2016)
Caulerpa racemosa	33-41	De Jesus Raposo *et al*. (2016)
Codium reticulata	39-67	De Jesus Raposo *et al*. (2016)
Enteromorpha spp.	33.4	Patarra *et al*. (2011)
Ulva sp.	38	De Jesus Raposo *et al*. (2016)
Ulva compressa	41.16	De Jesus Raposo *et al*. (2016)
Ulva lactuca	29-55.4	De Jesus Raposo *et al*. (2016; Wong and Cheung (2000)
Ulva pertusa	52.1	De Jesus Raposo *et al*. (2016)
Ulva reticulata	65.7	De Jesus Raposo *et al*. (2016)
Ulva rigida	38-41	De Jesus Raposo *et al*. (2016)

*Data compiled by Raposo *et al.* (2016)

microbiological culture media (Mendes *et al*., 2024). In addition to polysaccharides, seaweeds are rich in vitamins such as vitamin A, C, E, and several B-complex vitamins, as well as essential minerals like iodine, calcium, magnesium, and iron. These nutrients contribute to various health benefits, including antioxidant, anti-inflammatory, and immune-boosting effects. The rich iodine content in seaweeds is particularly beneficial for thyroid function, helping to regulate metabolism (Smyth, 2021). Seaweeds also contain other bioactive compounds such as polyphenols, carotenoids, and phlorotannins. Additionally, the

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antioxidants found in seaweeds, like polyphenols and carotenoids, contribute to their anti-inflammatory and anti-aging properties, which can help reduce the risk of chronic diseases such as cardiovascular disease, diabetes, and certain cancers (Pangestuti and Kim, 2011). The high fiber content in seaweeds, particularly soluble fiber, plays a crucial role in digestive health by promoting regular bowel movements, improving gut microbiota composition, and helping to regulate blood sugar levels and cholesterol. This combination of polysaccharides, vitamins, minerals, and fiber underscores the nutritional importance of seaweeds and their potential as functional food ingredients (Peñalver *et al*., 2020).

3. Seaweeds as prebiotic sources

Prebiotics are defined as non-digestible food ingredients that selectively stimulate the growth and activity of beneficial microorganisms in the gut, particularly bifidobacteria and lactobacilli, which are key to maintaining a healthy gut microbiome. To be classified as a prebiotic, a compound must resist digestion in the upper gastrointestinal tract, reach the colon intact, be fermentable by the gut microbiota, and selectively promote the growth and activity of beneficial bacteria (Rolim, 2015). Common characteristics of prebiotics include their ability to improve gut health, enhance the immune system, and produce SCFAs like butyrate, propionate, and acetate during fermentation. These SCFAs play a crucial role in maintaining the integrity of the gut lining, regulating inflammation, and providing energy to colonocytes, which are the cells that line the colon (Ma *et al*., 2022).

Seaweed-derived polysaccharides, such as alginate, carrageenan, and agar, act as prebiotics by fulfilling these criteria. These polysaccharides resist enzymatic breakdown in the stomach and small intestine, allowing them to reach the colon, where they are fermented by the gut microbiota. The fermentation process selectively promotes the growth of beneficial bacteria, leading to a healthier and more diverse gut microbiome, as shown in Figure 1 (Rini, Xu and Suzuki, 2024). The prebiotic effects of seaweed-derived polysaccharides have been extensively studied in both *in vitro* (laboratory-based) and *in vivo* (animal and human-based) settings, providing robust evidence of their health benefits. *In vitro* studies, which often involve simulating the conditions of the human digestive system, have demonstrated that seaweed polysaccharides such as alginate, carrageenan, and agar can be fermented by beneficial gut bacteria like bifidobacteria and lactobacilli (Bouillon *et al*., 2022; Oliyaei *et al*., 2022). The impact on gut microbiota composition is significant, as a healthy and balanced microbiome is associated with improved digestion, better immune function, and protection against gastrointestinal disorders such as irritable bowel syndrome (IBS) and inflammatory bowel disease (IBD). Moreover, the SCFAs produced during the fermentation of these polysaccharides have systemic effects beyond the gut, including regulation of glucose metabolism, reduction of systemic inflammation, and potential modulation of the gut-brain axis, which could influence mental health (Makki *et al*., 2018). Additionally, *in vitro* experiments have highlighted the selective stimulation of beneficial bacteria over harmful pathogens, suggesting that seaweed polysaccharides can contribute to a healthier and more balanced gut microbiome. These findings provide a strong foundation for further research and application of seaweed-derived prebiotics in functional foods and dietary supplements.

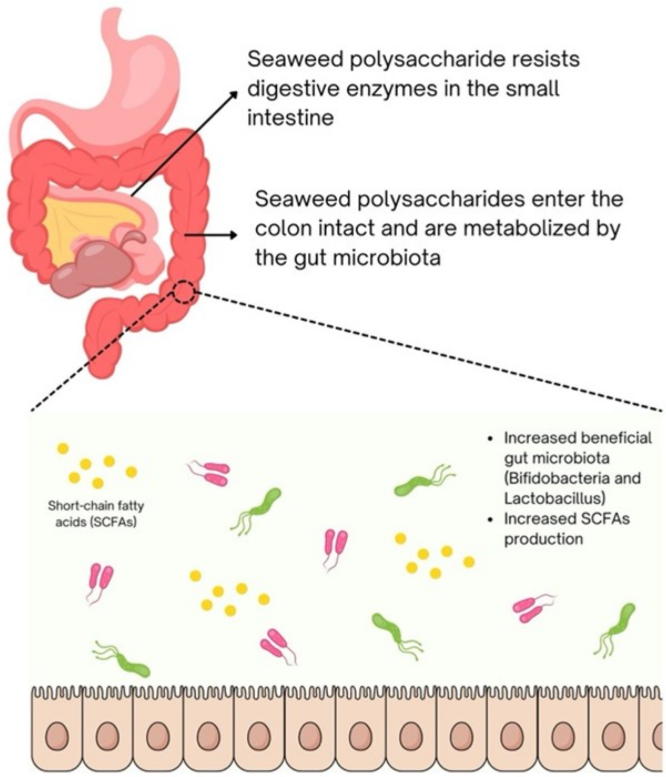

Figure 1. Seaweed polysaccharides resist digestion in the stomach and small intestine, thereby allowing fermentation in the colon. This process selectively enhances beneficial gut bacteria, which in turn supports a healthier gut microbiome.

In vivo studies have further validated the prebiotic potential of specific seaweed species. For example, studies on *Laminaria japonica*, a type of brown seaweed, have shown that its alginate content can increase the abundance of beneficial gut bacteria while reducing the presence of harmful bacteria in animal models (Gao *et al*., 2022). Similarly, *Porphyra yezoensis*, a red seaweed, has been shown to have prebiotic effects in animal studies, leading to improved gut health and enhanced immune responses (Wei *et al*., 2023). In human clinical trials, *Undaria pinnatifida* (wakame) has demonstrated the ability to modulate the gut microbiota composition,

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resulting in increased levels of bifidobacteria and lactobacilli (Yoshinaga *et al*., 2018). These studies underscore the potential of seaweed species as effective prebiotic sources, offering promising avenues for developing new functional foods that support gut health. The evidence from both *in vitro* and *in vivo* studies highlights the versatility and effectiveness of seaweeds in promoting a healthy microbiome, reinforcing their role as a valuable resource in nutrition and health.

Utilizing seaweeds as prebiotics presents both challenges and opportunities. The primary challenges include the variability in seaweed polysaccharide composition, which affects consistency in prebiotic effects, and potential safety concerns like heavy metal contamination. Despite these hurdles, there are significant opportunities to enhance the prebiotic potential of seaweeds through advanced processing and extraction techniques, such as enzymatic hydrolysis and novel extraction methods, which can improve the fermentability and concentration of bioactive compounds. Additionally, the development of seaweed-based synbiotics offers promising potential for more effective gut health products, highlighting the broader potential of seaweeds as sustainable, natural sources of prebiotics in the food and nutraceutical industries.

4. Applications of seaweeds in the food industry

Seaweeds have long been a staple in the culinary traditions of various cultures, particularly in coastal regions where they are abundant, as shown in Table 2. In Asia, seaweeds like nori, kombu, and wakame are integral to dishes such as sushi, soups, and salads. Nori, for instance, is widely used as a wrap for sushi rolls, while kombu serves as a fundamental ingredient in dashi, a Japanese broth essential to many recipes. Wakame is often found in miso soup and salads, prized for its delicate texture and nutritional content. In Korea, gim (a type of nori) is seasoned and roasted, commonly enjoyed as a snack or as an accompaniment to rice dishes. In Europe, especially in Ireland and Scotland, seaweeds like dulse and carrageen have been traditionally harvested and used in various dishes. Dulse, known for its salty flavor, is eaten raw, dried, or added to soups and stews, while carrageen is used to thicken puddings and other desserts (Tiwari and Troy, 2015; Fleurence, 2016; Figueroa *et al*., 2023).

Fermentation and drying are traditional methods of preserving seaweeds, enhancing their flavors, and extending their shelf life. Fermented seaweeds, such as the Korean kimchi made with sea mustard, offer not unique taste profiles but also additional probiotic benefits (Lee *et al*., 2023). In Japan, kombu is sometimes fermented to create a rich umami seasoning known as "kombucha," not to be confused with the fermented tea beverage (Abachi *et al*., 2022). Dried seaweeds are common across many cultures, providing a concentrated source of nutrients that can be easily rehydrated and used in cooking. For example, dried nori sheets are essential in sushi making, while dried kelp is often added to broths for its deep, savory flavor. These traditional uses highlight the versatility of seaweeds in culinary applications, reflecting their cultural significance and nutritional value across different regions (Sinurat *et al*., 2022).

Innovative food products incorporating seaweeds have gained significant attention in the functional foods and dietary supplements market, driven by the growing demand for natural and health-promoting ingredients (Tiwari and Troy, 2015). Seaweeds are increasingly being used in functional foods due to their rich content of bioactive compounds, including polysaccharides, vitamins, minerals, and antioxidants, which contribute to a range of health benefits such as improved gut health, enhanced immune function, and reduced inflammation. These products include seaweed-infused snacks, energy bars, beverages, and meal replacements that cater to health-conscious consumers seeking natural ways to boost their nutritional intake. In the realm of dietary supplements, seaweed extracts are being formulated into capsules, powders, and tablets, often marketed for their high iodine content and prebiotic properties (Roohinejad *et al*., 2017; Qin, 2018).

Modern food products are also leveraging seaweed-based prebiotic ingredients to enhance gut health. These include seaweed-enriched breads, cereals, meat, and dairy alternatives, where seaweed polysaccharides like alginate and carrageenan not only improve the texture and stability of the product but also provide prebiotic benefits by promoting the growth of beneficial gut bacteria (Cofrades *et al*., 2013, Cofrades *et al*., 2017; Lu and Chen, 2022). Consumer acceptance of seaweed-based foods is strongly influenced by the growing market demand for natural and sustainable food ingredients, as more people seek out products that align with health-conscious and environmentally responsible lifestyles (Anusha Siddiqui *et al*., 2023). The shift towards plant-based diets and functional foods has increased the popularity of seaweed as a versatile, nutrient-rich ingredient that offers both health benefits and a low environmental footprint (Pereira *et al*., 2024).

5. Conclusion and prospect

Seaweeds hold significant potential as sustainable prebiotic sources with applications in functional foods and nutraceuticals. While *in vitro* and *in vivo* studies

Table 2. Application of seaweed in food products.

Food product	Type of seaweed	Description	References
Nori (dried sheets of laver)	*Neopyropia tenera, Neopyropia yezoensis, Pyropia columbina,* and *Porphyra umbilicalis*	• Traditionally used to wrap rice balls with vegetables in sushi rice. • Incorporated into ready-to-eat foods like wine, instant soup, and jam to boost their nutritional value.	Kasimala *et al*. (2015); Kumar *et al*. (2021)
Kombu	*Saccharina latissima*, *Saccharina japonica*, *Saccharina angustata*	• Commercially, *kombu* is sold dried and rehydrated before use • Commonly added to soups, salads, and condiments.	Kasimala *et al*. (2015); Kumar *et al*. (2021)
Wakame	*Undaria pinnatifida*	• Incorporated into soups like miso soup in Japan and served as side salads with tofu.	Kasimala *et al*. (2015); Kumar *et al*. (2021)
Sea lettuce	*Ulva lactuca, Ulva rigida, and Ulva lactuca*	• Consumed in raw form or in soup preparations	Kasimala *et al*. (2015)
Seaweed soup		• Instant seaweed-vegetable soup with ingredients (cereals, legumes, and seaweed extracts (agar or carrageenan)	Jayasinghe and Pahalawattaarachchi (2016)
Seaweed chocolate	*Ulva reticulata*	• A high-iron chocolate infused with green seaweed, which contributes 40–50% of its total mineral content.	Thahira Banu and Uma Mageswari (2015)
Seaweed Pickle, *Pakoda*, and *Halwa*	*Eucheuma, Ulva reticulata, and Sargassum wightii*	• Dry seaweed powder was incorporated in various concentrations.	Sumayaa and Kavitha (2015)
Seaweed spices	Red seaweed *Eucheuma*	• A spice adjunct formulated with edible red seaweed as a key ingredient.	Senthil *et al*. (2011)
Seaweed pasta	*Undaria pinnatifida* and *Sargassum marginatum*	• Formulated pasta incorporating Japanese wakame (*Undaria pinnatifida*) and Indian brown seaweed (*Sargassum marginatum*), exhibiting enhanced functional properties and consumer acceptability.	Prabhasankar *et al*. (2009)
Seaweed noodle	*Monostroma nitidum*	• Incorporation of green seaweed powder in various proportions with or without eggs for the development of noodles.	Chang and Wu (2008)
	Gracilaria seaweed	• Seaweed powder for the development of alkaline noodles that are rich in fiber and have high nutritional value.	Keyimu (2013)
Seaweed Wafer, Porridge, Jelly, jam	*Hydropuntia edulis* and *Ulva lactuca*		Kumar *et al*. (2021)
Seaweed Coffee	*Sargassum wightii*	• Coffee brewed from Indian brown algae with 1%, 3% and 5% algae powder.	Kumar *et al*. (2019)
Seaweed Cookie and Sauce	*Ulva linza, Codium fragile, Sargassum fulvellum, and Sargassum fusiforme*	• Cookies with 5% seaweed powder matched the control in spread, moisture, and flavor, effectively masking the fishy odor.	Oh *et al*. (2020)
	Brown seaweed *(Gongolaria abiesmarina)*	• Brown seaweed was used in cookie and sauce preparation, with 3% in cookies and 2% in sauce deemed acceptable.	Afonso *et al*. (2020)
	Ulva sp.	• Biscuits enriched with *Ulva* sp.	Perdani *et al*. (2024)
Analogue rice	*Eucheuma cottoni*	• Analogue rice made from arrowroot (*Maranta arundinacease*) and seaweed flour fortified with fish collagen	Darmanto *et al*. (2022); Darmanto *et al*. (2024)
Edible coating	*Kappaphycus alvarezii*	• Seaweed-based edible coating to increase the overall quality and shelf life of minimally processed mango fruit	Siringul and Aminah (2023)
Purula (rice seasoning product)	Brown and green algae	• Rice seasoning for anemia from soy protein hydrolysate and seaweed	Kahfi *et al*. (2023)

https://doi.org/10.26656/fr.2017.10(2).272

support their benefits, further clinical trials are needed to confirm their effects on gut health, metabolism, and overall well-being. Additionally, safety concerns regarding heavy metal accumulation must be addressed to ensure long-term consumption safety. Technological advancements, such as enzymatic modification and precision fermentation, can enhance the bioavailability of seaweed-derived prebiotics, making them more effective. From a sustainability perspective, seaweed farming offers environmental benefits, but large-scale cultivation requires responsible management to prevent ecological disruption. Future research should focus on optimizing processing techniques and conducting clinical studies to validate health claims. Industry efforts should improve the formulation of seaweed-based functional foods to meet consumer demand for natural and sustainable products. Additionally, policy support and interdisciplinary collaboration are crucial to integrating seaweed into global food systems, promoting both health and environmental sustainability.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

We acknowledged Universitas Pembangunan Nasional Veteran Jawa Timur for its funding of research.

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