Food and Bioprocess Technology (2023) 16:1873–1903
https://doi.org/10.1007/s11947-023-03023-2

REVIEW

Exploitation of Seaweed Functionality for the Development of Food Products

Anuj Kumar[1,3] · **Mandakini Devi Hanjabam**[1,2] · **Pankaj Kishore**[1] · **Devananda Uchoi**[1] · **Satyen Kumar Panda**[1] · **Chitradurga Obaiah Mohan**[1] · **Niladri Sekhar Chatterjee**[1] · **Aliyamveetil Abubacker Zynudheen**[1] · **Chandragiri Nagarajarao Ravishankar**[1,4]

Received: 28 August 2022 / Accepted: 7 February 2023 / Published online: 20 February 2023

Abstract
Salubriousness, sustainability, low environmental footprint, and low production cost make seaweed an exciting food source for meeting food security and nutritional challenges. Seaweeds are increasingly being utilized in various food systems to avail dietary benefits for human health. The supplementation of seaweed with foods imparts its nutritional, techno-functional, and sensory functionalities to the food product. Thus, seaweeds present an interesting prospect to design tailor-made novel food products which are healthy, palatable, and at the same time 'convenience food'. The utilization of seaweeds for the development of food products is an excellent opportunity for food scientists, technologists, and phycologists for optimal exploitation of this food resource. The appropriate usage of seaweed in food systems could possibly give rise to a novel segment of seaweed-based composite/hybrid health foods. The review briefly summarises the trend and opportunities of seaweed utilization in functional food systems and the modifications occurring in food products upon supplementation with seaweed. Further, the review also discusses food safety concerns such as the presence of toxins, microplastics, heavy metals, and micropollutants in seaweed and challenges in adoption due to neophobia.

Keywords Seaweed utilization · Nutritional functionality · Technological functionality · Sensory functionality · Seaweed contaminants · Neophobia

Introduction

Food security challenges arising from population explosion, climate change, depleted land, and freshwater sources, and the global burden of non-communicable and lifestyle diseases have forced researchers and scientists to look beyond the conventional sources of food and nutrition. There is a constant pursuit for novel, sustainable, and salubrious sources of food that can address these concerns. The seaweed/marine macroalgae appear to be a sustainable nutritional food source with numerous physiological benefits. The consumption of seaweed has gained considerable attention in recent years, and even these aquatic plants have been described as the 'food of the future' (Neto et al., 2018). Therefore, considerable research and exploration are taking place for using seaweeds and the derived ingredients for their amalgamation into the human diet.

Seaweeds are macroscopic and predominantly marine algae found from the intertidal zone to 300 m deep (Levine, 2016). These marine plants are fast-growing –can grow up to 60 m in length– and have diverse habitats (Pina-Pérez et al., 2017). They do not require arable land, freshwater, and fertilizers for their growth (Tiwari & Troy, 2015) and can be cultivated in massive amounts in oceans. Currently, most aquatic plants are farmed (around 97%), and half of the produce is used for human consumption (Costello et al., 2019). According to the FAO report (2021), the world capture production of aquatic plants (majorly seaweeds) was 1.1 million tonnes in 2019, while the aquaculture production was 34.7 million tonnes. The primary producer countries identified

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✉ Mandakini Devi Hanjabam
mandakinicife@gmail.com

[1] ICAR-Central Institute of Fisheries Technology, Kochi 682 029, India

[2] Present Address: ICAR-CIFE, Kolkata Centre, Kolkata 700 091, India

[3] ICAR-IIWBR, Karnal 132 001, India

[4] ICAR-CIFE, Mumbai 400 061, India

are China, Indonesia, the Korea Republic, the Philippines, and Democratic People's Republic of Korea. The seaweeds are classified mainly into three subclasses–brown (Phaeophyta), green (Chlorophyta), and red (Rhodophyta), based on the significant pigment present (Hanjabam et al., 2019; Pandey et al., 2020). The primary pigments are fucoxanthin and chlorophyll a and c in brown seaweeds, chlorophyll a and b in green seaweeds, and phycobilins along with chlorophyll a and d in red seaweeds. The production of brown, red, and green seaweeds in 2019 stood at 16.4 million tonnes, 18.3 million tonnes, and 0.16 million tonnes, respectively (FAO, 2021). The consumption of seaweeds, per se, is not a new phenomenon. Seaweeds have been a part of the human diet for ages. Evidence tells us about their usage back 14,000 years in Chile for food and medicine (Dillehay et al., 2008). The seaweeds are commonly consumed as fresh, dried, or as an ingredient in Asian (China, Japan, Korea, Taiwan, Singapore, Thailand, Vietnam, Brunei, Cambodia) as well as other nations (South Africa, Indonesia, Malaysia, Belize, Peru, Chile, the Canadian Maritimes, Scandinavia, South West England, Ireland, Wales, California, the Philippines, and Scotland) around the world (Kılınç et al., 2013).

Seaweeds, aptly referred to as sea vegetables (Morrissey et al., 2001), are an important source of various dietary components. These aquatic plants contain low amounts of lipids but are an attractive source of protein, dietary fibre, and micronutrients (Moss & McSweeney, 2021). Seaweeds possess a wide range of bioactive compounds and metabolites with host physiological benefits, which are presented in Table 1. The presence of the bioactives (physiologically active agents) makes seaweeds an effective weapon against a host of non-communicable and lifestyle diseases and, thus, one of the most preferred options for the development of functional and health foods. Table 2 enlists the health benefits of these seaweed bioactives.

The current utility of seaweeds includes developing new food products and obtaining relevant high-value ingredients for food and pharmaceutical purposes. Seaweed or the compounds isolated from these plants can perform various roles in food systems–preservative, pigment, nutritional/bioactive agent, and technological improver (Barba, 2017). Further, the low cost, sustainability, and low environmental footprint make seaweeds relevant in changing scenarios for optimal utilization of their functionality for dietary benefits. Supplementation by seaweeds is expected to perform nutritional, technological, or organoleptic functions in the desired food product and alter the food product's nutritional content, technological functionality, and organoleptic attributes. Seaweeds can be utilized to tailor various food products' functional and technological attributes to our requirements for healthy, palatable, and convenience foods. The present review briefly discusses the utilization of seaweeds in food product development during the last decade. The review also highlights significant concerns associated with the acceptance and consumption of seaweed in the diet.

Table 2 Health benefits of bioactives found in seaweed

Antioxidant properties	Anti-ageing effects
Immune-regulatory effects	Antiosteoporosis effects
Anti-cancerous	Antidepression properties
Lowering blood cholesterol	Memory enhancement
Cardiovascular health	Antiacne effects
Anti-diabetic effects	Breastfeeding improvement
Antifatigue properties	Skin whitening effects
Antimicrobial attributes	Slimming properties
Anti-inflammatory properties	Suppression of oesophageal reflux
Anticoagulant properties	Prevention of goitre
Improved bowel functioning and gut health	

Adapted from Déléris et al. (2016); Wang et al., (2017); Qin (2018); Pandey et al. (2020)

Utilization of Seaweed Functionality in Foods

The seaweeds can be added to food matrices by supplementation either in the form of suitable extract/ingredient or whole. The incorporation presumably alters the food's technological, nutritional, and sensorial characteristics, thus

Table 1 Major bioactives found in seaweeds

Carbohydrates: sulphated and non-sulphated polysaccharides (fucoidans, fucans, laminarin, alginates, carrageenans, porphyrans, ulvans, phycarine, floridoside)

Lipids: PUFAs, MUFAs, phospholipids, glycolipids, ω-3 fatty acids

Pigments: chlorophyll, phycocyanin, phycoerythrin, phycobilin, carotenes, xanthophylls (siphonaxanthin, fucoxanthin, violaxanthin, zeaxanthin, lutein, zeaxanthin, neoxanthin)

Secondary metabolites: phytol, meroterpenoids, plastoquinones, phytosterols, fucosterols, phenolic acids, phloroglucinols, phlorotannins, flavonoids, phenolic terpenoids

Minerals: iron, magnesium, iodine, manganese, sodium, potassium, zinc, phosphorus

Vitamins: A, $B_{complex}$ (B_1, B_2, B_3, B_5, B_6, B_7, B_9, B_{12}), C

Holdt & Kraan (2011); Hamid et al. (2015); Koutsaviti et al. (2018); Circuncisão et al. (2018); Wells et al. (2017); Polat et al. (2021)

giving rise to new/novel foods having desired attributes. Roohinejad et al. (2017) have highlighted the application of seaweed and seaweed extracts to develop various categories of new food products. Along these lines, we have witnessed the development of various food products via seaweed supplementation during the last few years. Table 3 depicts the modifications occurring in food functionality upon seaweed incorporation. In other words, seaweed imparts its functionality to the food and, thus, customizes the food features. While the supplementation in 'whole' or 'extracted form' might modify the techno-functional attributes along with nutritional and sensorial behaviour, addition in the form of extract may have more impact on the nutritional/sensorial nature rather than the techno-functionality of the food.

Nutritional Changes in Food Products

The onset of lifestyle diseases has caused the consumer to gravitate towards food providing additional nutritional and disease-preventing qualities. These so-called functional foods have invigorated the world's food industry. Functional foods are that food which imparts enhanced health benefits beyond the basic nutritional attributes. These foods should be consumed as a part of the daily diet (Lagouri, 2018). The presence of a large number of bioactive substances (Table 2) in seaweeds makes them the preferred functional component for developing functional foods. Exploiting the bioactive compounds in seaweed, several seaweed-based ingredients and food products have been developed and marketed commercially. Prominent seaweed-based food products and functional ingredients that are sold commercially are presented in the supplementary information file.

A perusal of Table 3 indicts that different food segments have been utilized as a carrier for seaweed/seaweed ingredients for enhancing nutritional functionality; among them, bakery, meat, and dairy formulations appear to be the foremost option to assimilate the dietary benefits of seaweed. Among the bakery items, biscuits, cookies, and bread are noticed to be the preferred choice for researchers for supplementation with seaweed. Kumar et al. (2018) studied the effect of sea grapes (*Caulerpa racemosa*) (Chlorophyta) (dried and powdered) supplementation (at 1–10% level) on the nutritional attributes of semisweet biscuits. The inclusion caused a significant increase in protein (7.69 to 9.01%), mineral (ash content 1.28 to 2.23%), and fibre content (0.30 to 1.83%) of biscuits. Further, supplementation also enhanced the bioactive potential of biscuits as exhibited by increased polyphenolic content and antioxidative capacity. The polyphenolic content, DPPH activity, ABTS activity, hydrogen peroxide radical scavenging activity, and ferric reducing power appreciated from 617 to 829 µg/g, 84.1 to 88.6%, 89.3 to 96.6%, 20.1 to 38.7%, and 0.29 to 0.41, respectively. Therefore, *C. racemosa* incorporation augmented the nutritive potential of biscuits by imparting its nutritional functionality. Arufe et al. (2019) incorporated brown seaweeds powder *Bifurcaria bifurcata* (BB), *Fucus vesiculosus* (FV), and *Ascophyllum nodosum* (AN) (Phaeophyceae) (at 3–9% level) in gluten-free cookies from chestnut flour. The phenolic content (as phloroglucinol) and DPPH scavenging activity of supplemented flours displayed a seaweed concentration-dependent gain. The phenolic content and scavenging activity of blends of BB-chestnut (206–419 mg/100 g; 18.5–43.8%), FV-chestnut (188–386 mg/100 g; 16.0–37.9%) and AN chestnut (282–622 mg/100 g; 24.7–48.6%) were higher than chestnut flour (155 mg/100 g; 16.9%) alone. However, after baking cookies exhibited a reverse trend, although not concentration-dependent. The phenolic level and DPPH activity of chestnut flour cookies (876 mg/100 g; 75.9%) were found to be superior to BB (769–646 mg/100 g; 72.8–68.5%), FV (746–672 mg/100 g; 71.0–68.0%), and AN (601–430 mg/100 g; 52.8–43.8%) supplemented cookies at all levels, except AN addition at 3% level (926 mg/100 g; 76.0%). Maillard reaction products and other compounds generated during baking have the potential to contribute to the antioxidative response of baked cookies. These compounds were possibly formed at a higher degree in chestnut flour cookies compared to seaweed-enriched cookies. The addition of seaweed might have delayed the Maillard reaction seaweed-incorporate samples because of their water-trapping ability hindering/subsiding the formation of the antioxidants during baking (Arufe et al., 2019). Jenifer and Kanjana (2019) studied the effect of *Ulva lactuca* (Chlorophyta) fortified (30%) biscuit consumption on the anthropometric profile of malnourished children after feeding 60 g biscuit as tea time snack along with a regular diet for 2 months. They observed improved anthropometric profile, viz., height, weight, mid-upper arm circumference (MUAC), body mass index (BMI), and BMI percentile of the subjects. Further, the mean serum total protein content of the children increased from 5.17 to 6.30 g/100 mL after the feeding trial. Similarly, Oh et al. (2020) supplemented cookies with freeze-dried powder obtained from *Ulva linza* (formerly *Enteromorpha linza*), *Codium fragile* (Chlorophyta), *Sargassum fulvellum*, and *Sargassum fusiforme* (formerly *Hizikia fusiformis*) (Phaeophyceae) at 5% level to enhance their nutritional potential. Hall et al. (2012) measured the effect *Ascophyllum nodosum* (0–4%) (Phaeophyceae)-enriched bread consumption on energy intake and nutrient absorption in healthy overweight male subjects. The incorporation increased the fibre content from 13.3 to 17.8%. The consumption also caused a significant reduction (16.4%) in energy intake at a test meal served after 4 h but did not affect the nutrient uptake. The energy reduction is beneficial in weight loss which further abates the risk of diabetes and hypertension in obese (Hall et al.,

Table 3 Supplementation of seaweed/seaweed ingredients in various food products

Food product	Seaweed/seaweed ingredients	Nutritional functionality	Technological functionality	Sensorial functionality	References
Biscuit	*Caulerpa racemosa* (sea grapes) (1%, 5%, 10%)	Enhanced polyphenolic content and antioxidant capacity; enhanced protein content, mineral content, dietary fibre	Increased water and oil absorption by flour, increased solvent retention capacities of flour; shrinkage in biscuits; dough formation hampered due to seaweed addition	Decreased organoleptic acceptability of the product at higher levels; decreased lightness, redness, and yellowness values	Kumar et al. (2018)
Bread	*Ascophyllum nodosum* 1–4%	Satiating ingredient, higher dietary fibre content; significantly lower energy intake at post-meal; no effect on nutrient uptake	–	Sensorily slightly acceptable	Hall et al. (2012)
Bread	Mix of seaweed *Cladophora* and *Ulva* 2.5–7.5%	Increase in protein and fibre content, decrease in lipid content	Change in specific volume, hardness of bread; no impairment of technological attributes	Increase in colour intensity of bread with increasing levels; not much difference in sensory acceptance levels	Menezes et al. (2015)
Bread	*Kappaphycus alvarezii* 2–8%	–	Increased water absorption of dough, development and stability time of dough; decreased stickiness of dough; firm bread-reduced loaf volume and bulk density	Decreased lightness and increased yellowness	Mamat et al. (2014)
Bread	*Palmaria palmata* protein hydrolysate	Renin inhibitory activity, iodine content	Reduced loaf volume, reduced crumb springiness and crumb cohesiveness, increased crumb hardness	Darker bread crust-reduced lightness, slight reduction in sensorial acceptability	Fitzgerald et al. (2014)
Dim sum wrappers	*Caulerpa racemosa* 1.5–6%	–	Decreased folding score, interference with starch gelatinization in the wrappers-water absorption by the seaweed	Decreased lightness value along with increased greenness and yellowness; increased seaweed flavour and reduced gelatinized flavour	Windrayani and Ekantari (2021)
Breadsticks	*Himanthalia elongata* (5–15% on flour basis)	Increased phenolic content, higher DPPH radical scavenging activity, enhanced dietary fibre content	Firmness of sticks increased with seaweed levels	Significant change in colour visuals of the breadsticks; decrement in sensory acceptability of the product	Cox and Abu-Ghannam (2013)
Biscuits	*Ulva lactuca* 30%	High protein content, good amino acid profile; positive effect of biscuit consumption on anthropometric profile of children		Good sensory acceptability	Jenifer and Kanjana (2019)

Table 3 (continued)

Food product	Seaweed/seaweed ingredients	Nutritional functionality	Technological functionality	Sensorial functionality	References
Instant fried wheat noodles	*Eucheuma cottonii* *5 g with microalgae flour*	Increased protein content, mineral content, and dietary fibre content	Decreased water absorption; no effect on swelling index and cooking loss; texture problems in noodles-significant breakage	Sensory characteristics affected-green colour noodles, fishy flavour-not appealing, noodle with *Eucheuma* and *Spirulina* (each at 5%) found best	Kumoro et al. (2016)
Cake	*Eucheuma powder* 5–20%	Improved dietary fibre content and mineral profile	Dense batter-prevents foaming; some stabilization to the cake foam; increased consistency/viscosity of the batter; increased *K* and decreased *n*-faster thinning with shear; at higher level seaweed may destroy the batter; batter lacks pore structure	More-dark yellowish and reddish crumb; quality decreased at higher concentration; unpleasant at higher concentrations; up to 10% addition possible without changing properties too much	Huang and Yang (2019)
Cookies	*Bifurcaria bifurcata*, *Fucus vesiculosus*, *Ascophyllum nodosum* 3, 6, 9%	Enhancement in antioxidative potential of cookies-total phenolic content and radical scavenging activity	Increased water absorption capacity with concentration-*Bifurcaria* strongly affects water absorption; seaweed addition interferes with DMTA profile	-	Arufe et al. (2019)
Extrudates	*Porphyra columbina* 1.7–5.2%	Increase in protein, ash, and dietary fibre content; no difference in IVPD; slight decrease in arginine and drastic increase in methionine content; increase in phenolic content and antioxidant activity; antihypertensive property	Decrease in torque, specific mechanical energy consumption, feed caudal expansion, and specific volume	Decrease in lightness and yellowness and increase in redness-colour liked by panelists; enhanced flavour score; no significant difference between the texture, smell and taste; 3.5% added extrudate most preferred	Cian et al. (2014)
Bread	*Kappaphycus alvarezii* *Undaria pinnatifida*, *Ulva Linnaeus* (0.5–1.5%)	Presence of various organic acids, increased dietary fibre content	No difference in swelling and volumes of the bread	Garlic utilized as flavouring agent in *Kappaphycus* breads; *Wakame* supplemented breads most preferred for flavour and taste; *Kappaphycus* bread got the most for texture; *Ulva* breads scored most on overall acceptability	Komatsuzaki et al. (2019)
Mille crepes cake	*Eucheuma cottonii* 2.5–7%	Increased fibre content	Increase in thickness level of crepes layer	Seaweed smell-fishy seaweed odour-and grainy texture at higher levels; decrease in sensory acceptability with addition; 5% supplementation most acceptable	Ningsih and Anggraeni (2021)

Table 3 (continued)

Food product	Seaweed/seaweed ingredients	Nutritional functionality	Technological functionality	Sensorial functionality	References
Biscuits	*Eucheuma cottonii* 5–15%	–	–	Reduced sensory acceptability-taste, flavour, appearance, and texture; reduced lightness and increased redness; 5% most preferred by panelists	Lestari and Sulistiyati (2019)
Cookies	*Sargassum fulvellum*, *Enteromorpha linza*, *Codium fragile*, *Hizikia fusiformis* 5%	Increased dietary fibre content	Changes in solvent retention capacity-water, lactic acid, sodium bicarbonate, sucrose; lowered cooking making quality; increased dough density and breaking strength of cookie; interference with gluten network	Decreased lightness value; seaweeds imparted their colour to cookies; decrease in the overall acceptability; fishy flavour in some samples; *Hizikia* cookies most preferred	Oh et al. (2020)
Corn snack	*Sirophysalis trinodis*, *Polycladia myrica aqueous extracts: 2–4% each*	Increased phenolic content, DPPH activity, metal chelating activity, reducing power and total antioxidant	–	Decrease in lightness and redness of the product; sensory scores similar to control; all samples were acceptable	Etemadian et al. (2018)
Bread	*Palmaria palmata* 5 g	Stimulates inflammation, increases serum triglycerides, affects thyroid functioning	–	-	Allsopp et al. (2016)
Soup mix powder	*Ulva lactuca* along with either carrageenan or agar	Increased mineral content- I, Mg, Ca, K, and protein content in comparison to market sample	Increased consistency of soup, reduced the *Sirophysalis trinodis Polycladia myrica* aqueous extracts: 2–4% dissolution rate	Non-significant reduction in overall acceptability; taste, colour, flavour reduced; orange yellowish colour	Jayasinghe et al. (2016)
Muffins	*Kappaphycus alvarezii* 2–10%	Decrease in protein, dietary fibre and ash content	Increase in hardness, decrease in springiness, height, and specific volume of muffins upon addition of seaweed	Increase in lightness and decrease in yellowness; decrease in sensory acceptability of the product; 2% seaweed-added muffins most preferred	Mamat et al. (2018)
Baked food product	*Sargassum wightii fucoidan*	Functional benefits of fucoidan	Reduced breaking strength, little variation in free moisture content of the product	No change in the sensorial behaviour of the baked product; liked very much by the sensory panelists	Hanjabam et al. (2018)
Half-smoked sausage	Brown algae (10, 15%)	Increased nutritional components	–	No negative effect on the shelf life; sensorially acceptable product-10% supplemented most desirable	Sălăgean et al. (2015)
Beef patties	*Undaria pinnatifida* (Wakame)	Increased ash content; decreased calorie content	Decreased thawing loss and cooking loss; higher moisture retention	–	López-López et al. (2011)

Table 3 (continued)

Food product	Seaweed/seaweed ingredients	Nutritional functionality	Technological functionality	Sensorial functionality	References
Pork patties	Sea mustard, green laver, seaweed fusiform Each at 1,2,4%	Increased ash content; decreased volatile basic nitrogen	Decreased cooking loss with increased seaweed levels	More juiciness, less springiness with seaweed addition	Jeon and Choi (2012)
Restructured poultry steaks	*Himanthalia elongata*	Increased dietary fibre content	Increased purge loss, reduced cooking loss, increased shear force-ease of handling; it could overcome the functional problems associated with low salt restructured products	Sensorially acceptable product; decrease in lightness and redness	Cofrades et al. (2011)
Reduced fat pork patties	*S. japonica* 1, 3, 5%	Higher mineral and carbohydrate content, increased dietary fibre content; reduced calorific value	Reduced hardness and chewiness; higher springiness; reduced cooking loss	Fat replacer; higher yellowness, decreased lightness and redness; highest overall acceptability at 1 and 3% level	Choi et al. (2012)
Fish surimi restructured product	*Ulva intestinalis* and sulphated polysaccharide (SP) 0.27% and 0.05%	Decreased protein content, enhanced ash content, lower TBARS value implying antioxidative effect in product	Less moisture loss than control; less cooking loss; softer texture; reduced chewiness, cohesiveness; SP more beneficial for textural attributed	Lower TBARS values upon storage, sensorily acceptable; darker product in case of seaweed and lighter upon addition of SP	Jannat-Alipour et al. (2019)
Meat patties	*Ulva lactuca*, *Ulva rigida*	Antioxidative effect	–	Darker colour	Lorenzo et al. (2014)
Sausage	*Kappaphycus alvarezii* 2–6%	Reduction in lipid oxidation-antioxidative effect	Increased hardness, chewiness and water-holding capacity of sausage; reduced cooking loss	Decreased lightness, increased redness	Pindi et al. (2017)
Liver pate	*Ascophyllum nodosum (AN)*, *Fucus vesiculosus (FV)*, *Bifurcaria bifurcata (BB)* extracts 500 mg/kg	Enhanced protein levels of pate, antioxidative nature of seaweed-added pate-similar to BHA added samples	–	Decreased lightness after storage in FV and BB added pate	Agregán et al. (2018)
Fish oil-enriched bars	*Fucus vesiculosus* extract	High total phenolic content, radical scavenging ability	Extracts possessed emulsifying properties	–	Karadağ et al. (2017)
Pork patties	*Fucus vesiculosus* extract 250–1000 mg/kg	Reduced protein degradation upon storage–antioxidative ability	–	Affected the colour-redness of meat; more retention of yellow colour; no improvement in surface discoloration and odour	Agregán et al. (2019)
Pork patties	*Laminaria digitata* extract 0.01–0.5%	Pro-oxidant effect on the patties	No effect on pH, water-holding capacity and cook loss of the product	Decreased redness of patties with increased seaweed levels upon storage; acceptable sensory quality at low levels	Moroney et al. (2013)

Table 3 (continued)

Food product	Seaweed/seaweed ingredients	Nutritional functionality	Technological functionality	Sensorial functionality	References
Beef patties	*Himanthalia elongata* *10–40%*	Enhanced fibre content; increased total phenolic content and DPPH radical scavenging activity	Decreased cooking loss with increased seaweed levels; decreased firmness-more tender patties. Better mouthfeel	Better overall acceptability of seaweed enriched patties; enhanced lightness value; enhanced shelf life of the product	Cox and Abu-Ghannam (2013)
Turkey sausage	*Cystoseira barbata extract* 0.01–0.4%	Contains phenolic compounds, fatty acids and sterols; antioxidative and antihypertensive property	–	–	Sellimi et al. (2018)
Fish jerky	*Sargassum wightii* 3–5%	Enhanced fibre, carbohydrate and mineral (ash) content; increased DPPH radical scavenging activity and phenolic content	Decreased shear force- less tensile strength	Reduction in lightness and yellowness of the product; Brown colour product; spongier and grassy flavour in the jerky upon seaweed addition	Hanjabam et al. (2017)
Yoghurt	*Sargassum wightii* derived fucoidan	Antioxidant properties	–	No adverse effect on sensorial characteristics	Kumar et al. (2020)
Quarg cheese	*Laminaria saccharina (kombu)*	Increased iodine content	–	Sensorily acceptable	Shrestha et al. (2011)
Fermented milks	*Gracilaria domingensis extract*	-	pH, titratable acidity-similar to control; no change in acidification pattern Higher firmness, consistency cohesiveness and viscosity index -potential texture modifier	–	Tavares Estevam et al. (2016)
Soft cheese	*Laminaria (kelp)* *0.2% (dried and hydrated)*	–	Rapid removal of cheese moisture during pressing; thick consistency of hydrated seaweed-added cheese; increased acidity levels	No reduction in organoleptic qualities. Greenish colour to cheese; dense texture; particle mouthfeel in hydrated seaweed-added cheese	Okhotnikov et al. (2020)
Camembert cheese	*Palmaria palmata Saccharina longicruris soluble extracts*	Ace inhibitory activity, oxygen radical absorbance capacity	–	–	Hell et al. (2018)
Yogurt	*Caulerpa racemosa* *30%*	Enhanced dietary fibre content, protein content, total phenolic content, and antioxidant activity	–	Reduced acidity and enhanced pH of the product; more sensory preference for CR fortified yoghurt than commercial one	Dewi and Purnamayati (2021)

Table 3 (continued)

Food product	Seaweed/seaweed ingredients	Nutritional functionality	Technological functionality	Sensorial functionality	References
Milk	*Ascophyllum nodosum* *Fucus vesiculosus* *extracts*	Phenolic content, DPPH radical scavenging activity, ferrous ion chelating capacity; no cellular antioxidant activity	–	Reduced lightness and enhanced yellowness and greenness value of milk supplemented with extracts; aqueous extract more acceptable than ethanolic extracts	O'Sullivan et al. (2014)
Yogurt	*Ascophyllum nodosum* *Fucus vesiculosus* aqueous and ethanolic extracts (0.25–0.50%)	Antioxidant activity; ethanolic extracts having more antioxidant activity; ferrous ion chelating activity found in digestate	Whey separation, pH not affected; change in modulus at the end of storage life	Decreased lightness and enhanced greenness and yellowness in the yoghurt; pH no effect; aqueous extracts more preferred sensorily	O'sullivan et al. (2016)
Coffee beverage	*Sargassum wightii* (1–5%)	Increase in flavonoid content and ferric reducing power; slight change in DPPH radical scavenging activity and phenolic content	Decrease in total soluble solids; increasing the concentration of seaweed in coffee samples decreased the, shear thickening (dilatant) tendency of the beverage but increased the consistency of beverage	Coffee-potential to mask the seaweed off flavour; no distinct colour change; 1% seaweed supplemented beverage most preferred	Kumar et al., 2019
Seaweed chocolate	*U. reticulata*	High iron content with enhanced bioavailability than control; significant increase in haemoglobin, total iron binding capacity, mean corpuscular haemoglobin, mean corpuscular volume, serum iron, and serum ferritin levels in the selected subjects	–	High acceptability then standard chocolate	Banu and Mageswari (2015)

2012). Menezes et al. (2015) developed bread fortified with biomass consisting of *Cladophora* sp. and *Ulva* sp. (Chlorophyta) (0–7.5%). The supplementation increased protein from 16 to 18% and fibre content from 1 to 2% and decreased lipid content from 17 to 12%. The macroalgal biomass contained 26.3% ash (db), 8.7% protein (db), 3.9% fibre, and 378.58 µg/g carotenoids. Komatsuzaki et al. (2019) incorporated various seaweeds, i.e. *Kappaphycus alvarezii* (Rhodophyta) (0.5–1.5%), *Undaria pinnatifida* (Phaeophyceae) (1%), and *Ulva Linnaeus* (Chlorophyta) (1%), to formulate fibre rich breads. Fitzgerald et al. (2014) utilized bread from wheat and wheat-buckwheat mix (70:30) as a carrier for delivering renin-inhibitory *Palmaria palmata* protein hydrolysate in the human diet. Formulated wheat bread and wheat-buckwheat mix bread retained the activity after baking and inhibited renin by 11.21% and 14.92%. The inhibitory activity of hydrolysate-enriched breads was significantly higher than respective control breads. Allsopp et al. (2016) carried out a human study and investigated the effect of *P. palmata*–enriched bread (5%) consumption on inflammation markers. The consumption increased serum C-reactive protein by 16.1%, triglycerides by 31.9%, and thyroid-stimulating hormone by 17.2%, thus indicating the role of seaweed in stimulating inflammation and altering serum triglyceride level and thyroid functioning. The impact of these changes on health was thought to be minimal since these parameters remained in the normal clinical range. Cox and Abu-Ghannam (2013) utilized dried *Himanthalia elongata* to increase the phytochemical content of breadsticks. The maximum level of phytochemical content as measured by total phenolic level and DPPH inhibition was obtained at 17.07% incorporation of *H. elongata*. The incorporation further increased the dietary fibre content from 4.65 to 7.95% in the optimized product.

Huang and Yang (2019) used *Eucheuma* sp. powder (0–20%) (fibre 69.3% and ash 13.1%) to enhance the dietary fibre level of sponge cake. The incorporation hiked the ash content by 32.6% and dietary fibre around three times compared to the control. Kumoro et al. (2016) utilized composite flour consisting *Kappaphycus cottonii* (formerly *Eucheuma cottonii)* (Rhodophyta) and microalgae (*Chlorella vulgaris* and *Arthrospira platensis*) for manufacturing instant fried wheat noodles. *K. cottonii* had higher ash (26.05%; 25.08%) and crude fibre content compared to the microalgae flour (7.12–9.19%; 8.03–10.10%). *K. cottonii* powder (0–7.0% was utilized for developing mille crepes cake for imparting dietary fibre (Ningsih & Anggraeni, 2021). The soup powder manufactured with *Ulva lactuca* (Chlorophyta) (2.5%) along with carrageenan and agar was found to contain elevated levels of minerals, especially I, Mg, Ca, K, and protein, compared to market samples (Jayasinghe et al., 2016). Etemadian et al. (2018) incorporated the nutritional functionality of aqueous extract of *Sirophysalis trinodis* and *Polycladia myrica* (Phaeophyceae) in corn-based snacks as seasoning material. Seasoning with the extracts of *S. trinodis* and *P. myrica* enhanced the phenolics, total antioxidant activity, DPPH radical scavenging activity, metal chelating ability, and reducing power compared to the control. The extrudates prepared by blending corn flour with *Pyropia columbina* (formerly *Porphyra columbina)* (Rhodophyta) displayed higher protein, minerals, and fibre content and elevated phenolic levels, antioxidant activity, and antihypertensive activity (Cian et al., 2014). The protein content increased from 8.92/100 to 9.60 g/100 g, ash content from 0.28/100 to 0.57 g/100 g, and total dietary fibre from 6.84/100 to 7.05 g/100 g. The extruded snack prepared with seaweed also exhibited higher dialyzability of ACE inhibitory compounds (41.0% ACE inhibition), phenolic content (0.83 mg gallic acid/g dialysate), and antioxidant capacity (36.6% DPPH inhibition, 2.4 mM TEAC, power reduction, and 99.4% copper-chelating activity) than extruded maize product (Cian et al., 2014).

Meat- and fish-based food products are considered a good source of proteins, but these foods lack dietary fibre and bioactive constituents, which are essential for providing additional health gains. Some of the commonly consumed meat and fish-based products, i.e., meat-/fish-based patties, sausages, and restructured products, have been studied after supplementation with seaweed by various researchers. The patties made with beef or pork meat have been incorporated with different seaweeds by various researchers, viz. *Undaria pinnatifida* (López-López et al., 2011), sea mustard, green laver, seaweed fusiform (Jeon & Choi, 2012), *Saccharina japonica* (formerly *Laminaria japonica*) (Phaeophyceae) (Choi et al., 2012), *Ulva lactuca*, *Ulva rigida* (Chlorophyta) (Lorenzo et al., 2014), *Fucus vesiculosus* extract (Agregán et al., 2019), *Laminaria digitata* extract (Moroney et al., 2013), and *Himanthalia elongata* (Phaeophyceae) (Cox & Abu-Ghannam, 2013). The inclusion of seaweeds in patties increased the mineral and dietary fibre content of the patties and provided them with enhanced polyphenols and antioxidative ability. Agregán et al. (2019) utilized the hydroalcoholic extract of *F. vesiculosus* (at 250–1000 ppm level) for improving the antioxidant status of pork patties made from oleogel. The phenolic content, ABTS activity, ORAC activity, DPPH activity, and FRAP activity of the dried extract were noticed to be 20 g phloroglucinol equivalent/100 g extract, 2111 µmol Trolox equivalent/g, 1598.5 µmol Trolox equivalent/g, 278.1 µmol Trolox equivalent/g, and 37.5 Trolox equivalent/g, respectively. Cox and Abu-Ghannam (2013) fortified the beef burger patties with blanched *Himanthalia elongata* (10–40%) for enhancing the phytochemical content and fibre levels. The incorporation of *H. elongata* significantly increased the dietary fibre (1.64 g/100 g fw in 40% seaweed patties), phenolic content (up to 28.11 mg GAE/100 g fw), and DPPH radical scavenging activity (up to 52.32%) of patties compared to the control.

Sellimi et al. (2018) prepared turkey sausage by incorporating *Gongolaria barbata* (formerly *Cystoseira barbata*) extract while decreasing the amount of nitrites. The incorporation bestowed the sausage with antioxidative and antihypertensive properties. The total phenolic, flavonoid, and tannin contents in dried extracts (ethanolic, methanolic, and aqueous) of *G. barbata* were found to be varying from 24.16 to 49.77 mg PGE/g, 3.67 to 15.29 mg QE/g (quercetin equivalent), and 11.60 to 25.27 mg PGE/g, respectively. Further, the extracts also displayed DPPH activity, ferric-reducing power, ferrous chelating activity, hydroxyl radical scavenging activity, and β-carotene bleaching inhibition activity. Jannat-Alipour et al. (2019) integrated *Ulva intestinalis* (at 27.7 g/kg) and extracted sulphated polysaccharide (at 5 g/kg) in a functional surimi restructured product from fish meat on flour replacement basis. *U. intestinalis* and its sulphated polysaccharide are considered to be good sources of insoluble and soluble fibre. Ulvan, a soluble sulphated polysaccharide found in green seaweeds, possesses various bioactivities including DPPH activity, reducing power, and macrophage stimulation (Rahimi et al., 2016). The protein and ash content of the restructured product formulated by blending with *U. intestinalis* (107.3 g/kg and 31.1 g/kg) and its sulphated polysaccharide (107.4 g/kg and 27.4 g/kg) was higher compared to control (103.8 g/kg and 25.5 g/kg). Hanjabam et al. (2017) tried to increase the nutritional functionality of formulated tuna fish jerky, a ready-to-eat dried meat product by assimilating brown seaweed, *Sargassum wightii* powder (at 0–5% level). The incorporation aided in increasing the fibre content from 0.91 to 2.49%, ash content from 9.84 to 12.05%, and total phenolic content from 1.08 to 1.32 mg GAE/g. The DPPH-based antioxidative ability of the jerky improved upon seaweed addition as seen by declining IC50 value (0.98 to 0.65 mg/mL). The fortified tuna jerky had higher levels of essential minerals like Ca, Mg, Mn, and Fe but reduced Zn levels. Karadağ et al. (2017) successfully enhanced the phenolic content and radical scavenging activity of fish oil-enriched bars by incorporating antioxidants from *Fucus vesiculosus.* The ethanol and acetone extracts displayed higher antioxidative efficiency in bars. The addition of these extracts assisted in improving the total phenolic content, radical scavenging activity, and regeneration of tocopherol (Karadağ et al., 2017). Similarly, the supplementation of *Ascophyllum nodosum*, *Fucus vesiculosus*, and *B. bifurcata* extracts at the rate of 500 mg/kg increased the antioxidative property of liver pate (Agregán et al., 2018). Other workers have also integrated seaweed into meat foods. Cofrades et al. (2011) made dietary fibre-enriched restructured poultry steaks by supplementing *Himanthalia elongata*. Similarly, brown algae (Sălăgean et al., 2015) and *Kappaphycus alvarezii* (Pindi et al., 2017) were incorporated to increase the nutritional functionality of sausage.

Milk products are considered the choicest option, which can be utilized as a carrier for non-dairy bioactive components (Ramakumar et al., 2015). The sheer number of dairy products helps in outreach; thus, milk products with incorporated bioactives can serve a more significant section of the human population. Few researchers have explored these products as the carrier of seaweed bioactives. Kumar et al. (2020) incorporated fucoidan extracted from *Sargassum wightii* to enhance the salubriousness of the yoghurt. The bioactivity of fucoidan depends upon its sulphate and fucose content, and it displays numerous bioactivities–anticoagulant, anti-tumour, antithrombosis, antivirus, antioxidation, and immune-modulation. The fucoidan-added yoghurt displayed DPPH radical scavenging activity (80.2%), metal chelating activity (67.2%), and ferric-reducing power (0.5). Similarly, Dewi and Purnamayati (2021) manufactured *Caulerpa racemosa* (Chlorophyta) paste (CR: water 1:9) fortified yoghurt. *C. racemosa* contains protein 19.72%, fibre 11.65%, and bioactive secondary phenolic and flavonoid metabolites. The fortified yoghurt displayed an increase in fibre (0.93 to 2.57%) and protein (2.35 to 2.60%) content along with phenolic content (0.04 to 0.11 mg GAE/g) and antioxidant activity (138.69 to 191.79 ppm).

O'Sullivan et al. (2014) manufactured enriched milk with extracts of *Ascophyllum nodosum* (aqueous and 80% ethanolic extract; AN_a and AN_e) and *Fucus vesiculosus* (60% ethanolic extract–FV_e) at 0.25% and 0.50% levels. The phenolic content, DPPH activity, and ferrous ion chelating activity of the extracts followed the order: phloroglucinol > FV_e > AN_e > AN_a, phloroglucinol > FV_e > AN_a > AN_e, and AN_e > AN_a > FV_e > phloroglucinol, respectively. DPPH radical scavenging activity of seaweed extract-supplemented milks was higher compared to control, and this activity remained stable during 11-day storage. The authors suggested the application of seaweed extracts as a stable antioxidant for milk and milk products. The DPPH activity of seaweed extract-enriched milks and milk digestates were similar, except AN_e where a significant decrease was noticed. The ferrous chelating activity for milk and digestates increased from 22.5 to 58.5% and 77.5 to 92.5%. But the antioxidant effect was not observed in Caco-2 cells. Milk and digestates were unable to provide protection against DNA damage in Caco-2 cells which might be attributed to changes in the antioxidant compound in seaweed extract under altered pH conditions. Further, O'Sullivan et al. (2016) utilized these extracts for incorporation in yoghurt. The seaweed extract-enriched yoghurt sample was similar in composition to the control sample. Akin to the previous study in milk, the DPPH activity of seaweed extract-supplemented yoghurt was higher compared to the control, and DPPH activity remained similar over 28 days of storage. The highest radical scavenging activity was observed in yoghurt enriched with *F. vesiculosus* extracts. But the enrichment did not change the cellular antioxidant activity of yoghurt and yoghurt digestates in Caco-2 cells. Tavares Estevam et al. (2016) fortified the fermented milks with *Gracilaria* *domingensis* (Rhodophyta) extract from its powder to boost the nutritional potential. The powder of *G. domingensis* was rich in fibre (63.46%), protein (10.06%), and ash content (11.25%). Hell et al. (2018) tried the development of functional Camembert-type cheese by incorporating flakes of *Palmaria palmata* (Rhodophyta) and *Saccharina longicruris* (Phaeophyceae) at 2% level. The seaweed flakes were added to Camembert soft cheese model curd (SCMC) before ripening. The protein, fibre, and ash content of *P. palmata* and *S. longicruris* seaweed were 10.34%, 40.87%, and 13.95% and 9.49%, 46.35%, and 34.37%, respectively. Further their extracts displayed ACE inhibitory and ORAC activity. The addition of seaweed flakes did not significantly alter the bioactivity. The ACE inhibitory activity of SCMC samples including control increased during the phase 1 of ripening process (14 °C at 90% RH for 10 days). During phase 2 of ripening (14 °C for 10 days), a decrease in ACE inhibition was noticed for *S. longicruris* added cheese, whereas in other samples (control and *P. palmata* added cheese), a stabilizing tendency was observed. ORAC activity was not seen in any cheese at initial day (0th day). The ORAC activity increased during both ripening phases. Shrestha et al. (2011) supplemented the quarg cheese with *Saccharina latissima* (formerly *Laminaria saccharina*) (Phaeophyceae), which increased the iodine content of the cheese sample. Similarly, Okhotnikov et al. (2020) recommended the incorporation of kelp powder (*Laminaria* sp.), as iodine source, for enhancing the salubriousness of soft cheese.

Kumar et al. (2019) studied the effect of infusing seaweed (*Sargassum wightii*) powder (1–5%) in coffee. The workers observed a non-significant increase in the total phenols from 2.817 to 2.969 mg GAE/100 mL, although at the initial level (1%) of addition, the phenolics decreased to 2.791 mg GAE/100 mL. The same trend was observed for total flavonoids which varied from 1.376 to 1.525 mg QE/100 mL. The binding of phenolics and flavonoids to milk protein was thought to be responsible for non-detection during the assay. The FRAP activity of seaweed increased from 176.19 µM Trolox/100 mL (control) to 210.86 µM Trolox/100 mL (5% addition). Contrarily, the DPPH activity decreased from 74.45% (control) to 71.47% (5% addition). The antioxidants present in seaweed-infused coffee might have interacted with ferric ions more effectively than DPPH radical, thereby showing the aforementioned effect. Banu and Mageswari (2015) studied the effect of green seaweed (*Ulva reticulata*)–enriched chocolate consumption on anaemic adolescent girls. The developed seaweed-based chocolate had 56 mg of iron/100 g and 11.80 mg of bioavailable iron. Further, the feeding experiment caused a significant increase in haemoglobin, total iron binding capacity (TIBC), mean corpuscular haemoglobin (MCH), mean corpuscular volume (MCV), serum iron, and serum ferritin levels in the selected subjects. TIBC indicates the improved iron status in the subjects. MCV–which indicates the volume occupied by the red blood cells–was maintained at an optimal level (82–89.9 m^3) after the feeding trial in the subjects. This presumably is due to the high iron content of *U. reticulata*. The iron content of this seaweed is about 40–50% of the total mineral content. Further, the bioavailability of seaweed-based chocolate was 10% higher than plain chocolate. Further, serum ferritin levels are correlated with the need for iron in the body, and a decrease in ferritin levels indicates iron deficiency.

The enhancement in the nutritional profile of the products prepared by incorporating seaweeds is presumably due to the high nutritional potential of the seaweed. The protein content in the seaweed varies from 5 to 47% (Shannon & Abu-Ghannam, 2019). In general, it should be noted that protein content is higher in green and red seaweeds than in brown seaweeds (Holdt & Kraan, 2011; Peñalver et al., 2020). Glutamic acid and aspartic acid are generally found in seaweeds (Holdt & Kraan, 2011). Taurine, an important but non-essential amino acid, is present in reasonable amounts in red algae (Wells et al., 2017). Further, seaweed proteins are better than plant proteins in terms of protein quality. *Undaria pinnatifida* has an amino acid score equivalent to that of an egg, i.e. 1.0 (Shannon & Abu-Ghannam, 2019). The protein yield of macroalgae is 2–5 times higher than wheat/legumes (Ummat et al., 2021). Dietary fibre is an important functional component present in food and is classified into soluble and insoluble fractions. The presence of dietary fibre is linked to the reduced energy density of foods. The dietary fibres include cellulose, hemicellulose, pectin, gums, and resistant starches. While the insoluble faction helps regulate GI movement, the soluble faction is important for various physiological functions, including inhibition of diabetes, cardiovascular diseases (Arshad et al., 2021), and colorectal cancer (Masrul & Nindrea, 2019). The dietary fibre ranges from 36 to 60% in seaweeds, with the soluble component being 55–70% (Peñalver et al., 2020). Red seaweeds generally have a higher proportion of soluble dietary fibre, while brown seaweeds have more insoluble dietary fibre (Holdt & Kraan, 2011). In terms of micronutrients, the seaweeds contain fat- and water-soluble vitamins A, D, E, K, C, B_1, B_2, B_9, and B_{12} and essential minerals like Ca, Fe, I, Mg, P, K, Zn, Cu, Se, and F (Qin, 2018). The fundamental reason behind the upsurge in seaweed exploitation is the presence of numerous physiologically active compounds, i.e. terpenes, acetogenins, alkaloids, phlorotannins, alkaloids, phloroglucinol, eckol, dieckol, fucidiphloroethol, catechin, gallic acid, sulphated polysaccharides, sulpholipids, and peptides (Pandey et al., 2020) (Table 2). These bioactives are responsible for seaweeds' pharmacological and functional benefits, i.e. anti-inflammatory, anti-lipidemic, anti-tumour, anti-diabetic, and antioxidative properties

(Table 3). Thus, the plethora of functional components and macro- and micronutrients make seaweed a viable choice to be incorporated into food systems for altering the nutritional functionality of the food products.

Technological Changes in Food Products

Seaweed incorporation in food, besides enhancing the nutritional benefits, also imparts its technological functionality. The techno-functional properties, i.e. viscosity, foaming, gel-forming ability, emulsion-forming ability, plasticity, dough-forming ability, and gelatinization, describe the behaviour of food ingredients during food processing (Awuchi et al., 2019). These functional properties of a food are governed by the compositional, conformational, and physicochemical attributes of the principal food components–protein, fat, and fibre–along with the processing/manufacturing process utilized for the food preparation. The behaviour of food ingredients during the preparation and cooking depends on these attributes and, in turn, affects the quality of the finished product (Awuchi et al., 2019).

Kumar et al. (2018) incorporated *C. racemosa* powder in wheat flour for biscuit preparation (0–10%). This led to increased water absorption capacity (WAC) and fat absorption capacity (OAC) of mix. WAC and OAC of 10% seaweed-wheat flour mix exceeded the absorption capacity of refined wheat flour by 22.5% and 27.5%. These capacities are a measure of the hydrophilic and lipophilic constituents of the flour. The solvent retention capacities (SRC) (lactic acid, sodium carbonate, and sucrose)–index of the swelling capacity of the flour components–of the flour also rose with increasing seaweed mix, except lactic acid SRC. The gain in sodium carbonate SRC and sucrose SRC was 16% and 20%, compared to the control. The incorporation of seaweed increased the spread ratio, presumably due to the decreased thickness of the biscuits formed and leading to decrement in the break strength of biscuits from 17.57 to 11.29 N. The addition might have restricted the formation of appropriate semi-sweet biscuit dough by interacting with gluten/gluten dilution and eventually impairing the dough machinability and causing shrinkage in biscuits. Villemejane et al. (2013) postulated that the presence of fibre restrains the dough development process and affects the physical attributes (spread, hardness) of the biscuits.

Similarly, Arufe et al. (2019) in their experiments on gluten-free cookies from chestnut flour-seaweed powder observed a seaweed concentration-dependent (3–9%) increase in the water absorption of flour enriched with *A. nodosum* (58.3–68.7%), *B. bifurcata* (62.4–70.4%), and *F.* vesiculosus (58.9–64.0), and the water absorption was superior compared to the chestnut flour (56.4%). Further, the dynamic mechanical thermal analysis (DMTA) profile, which describes the viscoelastic attributes of the food material by deforming it as a function of temperature (Sablani et al., 2010), was altered as a result of seaweed addition, implying a change in storage modulus, loss modulus, and mechanical loss factor of the dough due to seaweed incorporation. The water absorption characteristics were found linked to the temperature range of phase transitions–gelatinization of starch (59–97 °C), melting of amylose (133–171 °C) and amylopectin crystallites (82–101 °C), and reversible dissociation of amylose-lipid complex (107–128 °C). Oh et al. (2020) observed variations in SRCs upon mixing seaweed powder (5%) (*S. fulvellum*, *U. linza*, *C. fragile*, and *S. fusiforme*) with wheat flour. Water SRC, sodium carbonate SRC, lactic acid SRC, and sucrose SRC of the blends varied from 58.85 (control) to 102.95% (*U. linza*), 60.82 (*C. fragile*) to 124.38% (*S. fulvellum*), 78.59 (*C. fragile*) to 110.43% (control), and 107.19 (*C. fragile*) to 168.47% (*U. linza*). Higher SRC values are associated with lower cookie quality. The addition of seaweed increased the dough density–reflects the air incorporated during mixing and enhanced air incorporation leads to better cookie quality–from 1.20 (control) to 1.21–1.23 g/ mL (seaweed), cookie moisture content from 1.16 (control) to 1.67–2.17% (seaweed), and breaking stress from 37.89 (control) to 39.03–55.07 N (seaweed). The spread ratio for biscuits decreased from 6.61 (control) to 5.62–6.18 (seaweed). They stated that the seaweed addition led to the decreased cookie-making quality of the flour. The dietary fibre present in seaweed is known to influence the baking quality of flour by interfering with the gluten network (Oh et al., 2020) and also increasing the cookie hardness (Mancebo et al., 2018). Adding fucoidan, a sulphated polysaccharide obtained from *Sargassum wightii* to the biscuits decreased the breaking strength of the baked food product (Hanjabam et al., 2018).

Mamat et al. (2014) found that admixing *K. alvarezii* powder (at 0–8% level) for bread preparation caused increased water absorption of the dough (from 58.53 (control) to 77.63% (8%)) and the development (from 8.33 (control) to 11.90 min (8%)) and stability time (from 6.73 min (control) to 11.73 min (8%)) of the dough. These parameters are related to the dough machinability and interfere with the products' attributes. The seaweed constituents contributed towards high water absorption via hydrogen bonding and other hydrophilic interactions. The stickiness of the dough varied from 37.55 to 41.52 g, and no significant effect was observed. The interaction of gluten protein with added components (Wang et al., 2022) and hydration of gluten proteins (van Velzen et al., 2003) can alter the stickiness of the dough. The bread loaf volume reduced from 1527 (control) to 1114 mL (8% seaweed), and the bread firmness increased from 284.73 (control) to 587.51 (8% seaweed), indicating that the density of bread was altered upon seaweed fortification. Similarly, a reduction in specific volume from 3.30 (control) to 2.68 mL/g (wheat bread) and 3.10 (control) to

2.54 mL/g (buckwheat bread) was recorded by Fitzgerald et al. (2014) in breads made via incorporating *Palmaria palmata* protein hydrolysate. The inclusion also led to an elevation in crumb hardness and depression in crumb cohesiveness and springiness in both wheat and buckwheat bread. The reduction in volume of bread could partly be attributed to competition between starch and added protein moieties for water, hindering the hydration and swelling of starch and consequently inhibiting the gelation. Menezes et al. (2015) also noticed the changes in specific volume and hardness of the bread upon the addition of powdered seaweed consisting of *Cladophora* sp. and *Ulva* sp. at 2.5–7.5% level. Cox and Abu-Ghannam (2013) studied the effect of dried *Himanthalia elongata* powder incorporation in breadsticks (5–15%) using the central composite design of response surface methodology. The incorporation led to a concentration-dependent increase in the hardness of breadsticks. The hardness (N/mm) of breadsticks varied from 69.85 to 108.8 N/mm. The maximum hardness was observed at 17.07% seaweed addition. Mamat et al. (2018) found that the effects of *K. alvarezii* powder addition (0–10%) in muffins were similar to the effects observed in bread. The hardness increased from 484.84 (control) to 1569.38 N (10% seaweed), while springiness, height, and specific volume of the muffins decreased from 0.75 (control) to 0.55 cm (10% seaweed), 53.33 (control) to 48.33 mm (10% seaweed), and 2.15 (control) to 1.80 cm^3/g (10% seaweed). The addition increased the batter density and reduced its rising tendency thereby impacting springiness and the specific volume of bread. A change in firmness could be attributed to increased density (reduction in volume) upon seaweed supplementation.

Huang and Yang (2019) manufactured sponge cake by supplementing *Eucheuma* powder (0–20%) in wheat flour. The addition of seaweed powder increased the specific gravity of the batter from 0.505 (control) to 0.559 g/cm^3 (10% seaweed), thus negatively impacting the foaming ability of the cake batter. This correlated well with an increased consistency index (K) from 15.65 (control) to 424.35 Pa s (10% seaweed) upon inclusion of the seaweed powder. The flow behaviour index reduced drastically at higher levels of seaweed addition (15–20%). The seaweed effects were well indicated by the reduction in the volume of cakes, i.e. from 931.27 to 864.47 cm^3. The addition of seaweed essentially negated the proper formation of the gluten 3D network and destroyed the batter system. The cake became dense with the addition of seaweed. The hardness and chewiness of the cake samples increased from 300.42 (control) to 689.46 g (10%) and from 228.74 (control) to 491.69 g (10%). The hardness and chewiness are negatively correlated to cake quality. The addition of seaweed altered the crumb appearance. The number and size of the crumb pores reduced after the addition of seaweed. The sponge cake quality did not vary much up to 10% level of seaweed addition, and above that cake quality reduced significantly.

Few researchers have studied the effect of seaweed addition in noodles (Kumoro et al., 2016), dim sum wrappers (Windrayani & Ekantari, 2021), soup (Jayasinghe et al., 2016), and extrudates (Cian et al., 2014). Kumoro et al. (2016) noticed significant breakage in instant wheat fried noodles with *Kappaphycus cottonii* and microalgae flour upon cooking. Although no effect was noticed on cooking loss and swelling index. Windrayani and Ekantari (2021) studied the effect of the addition of *C. racemosa* (1.5–6.0%) on dim sum wrappers. The addition reduced the folding scores of the wrappers prepared by interfering with the starch gelatinization process. Jayasinghe et al. (2016) manufactured soup-mix powder with *Ulva lactuca*, carrageenan, or agar. The soup prepared from them had higher consistency and viscosity because of the thickening effect of the seaweed polysaccharides. Cian et al. (2014) combined red seaweed *Porphyra columbina* (1.7–5.2%) with maize grits to form an extruded product in a single screw extruder. An increase in the level of seaweed decreased the torque (UB) from 600.1 (control) to 325.1 (5.2% seaweed), feed caudal (g/min) from 98.9 (control) to 87.7 (5.2% seaweed), specific mechanical energy consumption expansion (J/g) from 56.1 (control) to 34.2 (5.2% seaweed), specific volume (cu.cm/g) from 7.3 (control) to 5.8(5.2% seaweed), and expansion of the products from 3.5 (control) to 3.2 (5.2% seaweed). The addition of seaweed reduced the friction, which led to this decrease in torque and energy consumption. Further, reduced friction also decreased the residence time, which governs the product's cooking. This can be seen in the reduced volume of the product. The presence of fibre components–seaweeds are a good source of fibres–is known to reduce the degree of cooking and expansion ratio (Cian et al., 2014).

López-López et al. (2011) manufactured low-salt and low-fat patties from beef incorporating *Undaria pinnatifida* (3%) powder. The thawing (1.92–3.28%; 0.32–1.00%) and cooking losses (27.61–34.34%; 10.69–21.08%) were observed to be higher in seaweed-free samples compared to seaweed-added samples, respectively. The reduced cooking loss could be related to the binding tendency of dietary fibre and minerals present in seaweeds indicating the potential usage of *U. pinnatifida* in water binding in low-salt meat foods. The added seaweed helped in preserving the nutritional quality of the beef patties by restricting the losses during processing. Similarly, Choi et al. (2012) studied the effect of *Saccharina japonica* powder (0–5%) addition on reduced-fat pork patties and observed reduced cooking losses. This might have occurred due to the presence of dietary fibres, alginate and laminarin, which possess high water-holding and binding capacity. Further, the seaweed incorporation led to changes in the hardness, springiness, chewiness, and cohesiveness of the patties. The binding and stabilizing attributes of *S. japonica* powder along with interaction with meat constituents altered the textural parameters of the reduced-fat pork patties. Akin to this Jeon and Choi (2012) also observed reduced cooking loss and increased juiciness in pork patties fortified with sea mustard, green laver, and fusiforme seaweed at 1–4% level. The lowest cooking loss was observed for patties with sea mustard (5–8%). The addition of seaweed also led to increased hardness and chewiness of the cooked patties. Moroney et al. (2013) studied the effect of spray-dried *Laminaria digitata* extract (0.01–0.5%). The extract did not significantly affect the water-holding capacity and cook loss of the pork patties probably due to the usage of extracts at very low levels. Beef patties made with powdered and blanched *Himanthalia elongata* (10–40%) displayed decreasing cooking loss with increasing seaweed levels. The control sample exhibited a loss of 40.28%, while in seaweed-fortified samples loss ranged from 33.88 to 34.80%, presumably due to the water-binding ability of its fibrous constituents–hydrocolloid effect. The hardness of fresh patties from all treatments was significantly different and varied from 17.50 to 19.06 N/mm. During the storage period of 1 month, the patties consisting of seaweed were significantly softer compared to the control. The hardness values at the end of the storage period for control were 40.23 N/mm, and for seaweed, samples varied from 21.33 to 28.44 N/mm (10–40%). The incorporation of carbohydrates and fibres in meat patties might assist in improving the yields and textures and reducing formulation costs (Cox & Abu-Ghannam, 2013). The restructured poultry steaks prepared with the addition of powdered *Himanthalia elongata* (sea spaghetti) (3%) had lower cooking loss due to their water-binding properties (Cofrades et al., 2011) and thus offer a potential solution to overcome technological problems associated with manufacturing low-salt products. Jannat-Alipour et al. (2019) manufactured fish surimi-based restructured products supplemented with *Ulva intestinalis* (powder) and sulphated polysaccharide, and the incorporation led to changes in cooking loss and textural attributes. The sulphated polysaccharide exerted a beneficial effect on the textural attributes. This could be attributed to the affinity of the seaweed and sulphated polysaccharides toward the water. The polar groups, i.e. (carboxyl, hydroxyl, and sulphate) attached to the sulphated polysaccharides, form hydrogen bonds with the water molecule and help in moisture retention (Shao et al., 2015). The changes in the texture of the food are also linked to the water retention properties (Pinero et al., 2008). Pindi et al. (2017) researched the effect of powdered *K. alvarezii* (0–6%) addition on chicken meat sausage. Seaweed addition significantly affected the hardness, cohesiveness, and chewiness of sausages. The water-holding capacity of chicken sausage varied from 10.38 (control) to 12.91% (6% seaweed). Similar to other studies, the cooking loss in the sausage decreased with addition of the seaweed powder from 1.06 (control) to 0.10% (6% seaweed). It should be noted that apart from the amount of dietary fibre, the solubility of fibre dictates the changes in textural attributes of meat products. Due to its water-binding ability, insoluble fibre from the seaweed possibly formed a rigid protein matrix structure through a 3D network of insoluble fibres (Barretto et al., 2015) and modified the texture of the food. Hanjabam et al. (2017) found that the tuna fish jerky prepared by adding powder of *Sargassum wightii* (3–5%) reduced the shear force required to cut the jerky sample from 7806.33 (control) to 6316.11 g (5% seaweed). The addition of seaweed might have interfered with protein cross-linking, which is essential for making a stable protein network and giving the product structural rigidity and consequently reducing the shear force in seaweed-supplemented jerky samples (Hanjabam et al., 2017).

Tavares Estevam et al. (2016) deliberated upon the texture-modifying properties of aqueous *Gracilaria domingensis* extract and compared it with gelatin. The aqueous extract (3 and 6 g powder in 200 mL) and gelatin improved the textural responses (firmness, consistency, cohesiveness, and viscosity index) in comparison to the control. The firmness (mN), consistency (mNs), cohesiveness (mN), and viscosity index (mNs) values for the control and gelatin-added fermented milks after fermentation period were found to be 128.3, 1165.5, 58.1, and 35.3 and 150.0, 1291.4, 75.7, and 48.8, respectively. The seaweed extracts incorporated samples (6 g) displayed enhanced values–172.2, 1469.4, 79.5, and 56.9–for the textural attributes (in the same order). The interaction of seaweed extract ingredients, viz. protein, with casein during the gel formation throughout the acidification process modified the textural attributes of the acidified milks. Further, agar, the main polysaccharide present in *Gracilaria* sp., is known to distribute homogenously in milk gels and exert hydrocolloid action. Tavares Estevam et al. (2016) further suggested aqueous seaweed extract as a bulking agent and texture modifier in fermented milks and other related dairy foods. Okhotnikov et al. (2020) prepared soft cheese incorporating dried and hydrated kelp powder (0.2%) before thermocyclic coagulation. The cheese incorporated with hydrated seaweed powder showed thicker consistency after the moisture removal stage. The removal of moisture took place at a rapid pace in seaweed-enriched samples during the pressing stage compared to the control. The mass fraction for dry matter for seaweed-added cheese was higher (42.21–42.28%) compared to the control (36.68%). As mentioned previously, O'Sullivan et al. (2016) utilized the extracts of *Ascophyllum nodosum* (aqueous and ethanolic) and *Fucus vesiculosus* (at 0.25% and 0.50% levels) for manufacturing yoghurt. They did not observe any significant difference in the whey separation of different yoghurts; the whey separation values varied from 14.7 to 21.4%. Further, the modulus values of all yoghurts were observed to be lower compared to the control, except AN_a and AN_e after the end of the storage period (28 days).

Kumar et al. (2019) performed rheology of the *Sargassum wightii* powder-infused coffee sample (0–5%) and observed that the flow behaviour index (*n*) of seaweed coffee samples decreased while the consistency index (*K*) increased, with increasing seaweed concentration. *K* and *n* values for the prepared seaweed-enriched coffee samples (1, 3, and 5%) were 1.34, 1.11, and 1.09 and 0.0036, 0.015, and 0.018, higher as compared to control (*K*- 1.385; *n*- 0.0003). The observed increase in the consistency index was majorly due to increased polysaccharide (soluble) and phenolic compounds due to seaweed addition. Interaction of these compounds with soluble solids led to decreased flow behaviour index–a decrease in the shear thickening behaviour of the coffee beverage. A perusal of the thermograms associated with the coffee samples pointed out that the addition of seaweed decreased the glass transition temperature from 163 (control) to 121.3 °C, 138.1 °C, and 139.3 °C (1, 3, and 5% seaweed). This shift was attributed to the changes in the sulphate polysaccharides and denaturation of protein with temperature. Further, Kumar et al. (2019) proposed that in coffee sample, breakage of hydrogen bonds and hydrophobic aggregation of proteins changed the enthalpy of coffee beverage upon seaweed infusion.

Sensory Changes in Food Products

The food is appreciated/despised by humans through their senses. Although, nowadays, consumers' behaviour is inclined toward health foods, but consumption and commercial success of the food product depends upon the sensory appeal of the food product (Stone, 2018). The sensory behaviour of food is important for the launch of a new product and its continual success in the market (Vivek et al., 2020). It further helps in understanding the product and its quality issues. Seaweeds because of the presence of numerous compounds and metabolites have their inherently unique taste and flavour. The presence of free amino acids and their amount are important factors governing the taste of seaweeds–sweet, sour, and bitter–and they are also known to contribute towards umami taste (Kawai et al., 2012). According to taste perception, Poojary et al. (2019) grouped the free amino acids into four: sweet (threonine serine, glycine, alanine, and proline), umami (aspartic acid and glutamic acid), bitter (valine, methionine, isoleucine, leucine, phenylalanine, histidine, arginine, and tryptophan), and tasteless (tyrosine and lysine). The seaweeds from Phaeophyceae impart umami/sweet taste, the principal free amino acids being glutamic acid, glutamine, and alanine. *Saccharina latissima*, *S. japonica*, *and P. palmata* are known sources of glutamate flavour (Chapman et al., 2015). The presence of glutamine and alanine gives sweet taste to *S. muticum* and *U. pinnatifida*, while the presence of glutamic acid, glutamine, and alanine in *Scytosiphon lomentaria* gives out both a sweet and umami taste. The seaweeds from Rhodophyta impart umami taste because of the presence of glutamic and aspartic acid. The major exception is *Chondrus crispus*, which because of high amount of phenylalanine (25%) is bitter in nature (Kawai et al., 2012), although the presence of moderate levels of glutamic should impart an umami taste. Kawai et al. (2012) observed that it is difficult to group Chlorophyceae based on taste. While the free amino acid profile of *Codium fragile* is similar to Rhodophyceae, *Ulva* sp. gives bittersweet responses because of large percentages of glutamine, alanine, and cysteine. Chapman et al. (2015) generated various sensory descriptors (flavour, taste, texture, and mouthfeel) for dried and steamed seaweed, viz. *P. palmata*, *S. latissima*, *Laminaria digitata*, and *Alaria esculenta*, to describe their organoleptic behaviour and then extracted 11 most frequent quality descriptors, viz. odour intensity, sourness, sweetness, saltiness, bitterness, umami, grassiness, liquorice flavour, sea association, chewiness, and crispiness, associated with seaweeds. Out of the four seaweeds evaluated, *L. digitata* was neutrally placed and used as a reference against other seaweed species. Peinado et al. (2014) evaluated pre-heated (70° C for 30 min) aqueous extracts (1%) of five different seaweeds, viz. *L. digitata*, *A. nodosum*, *Pelvetia canaliculata*, *F. vesiculosus*, and *F. spiralis* for sensory behaviour using a non-structured scale (0–10). The sensory descriptors were honey-like odour, herbal odour, seaweed-like odour, seafood-like taste, saltiness, bitterness, green tea-like taste, and salmon-like taste. *Laminaria* sp. extract was identified to possess intense seaweed-like aroma, mildest honey aroma, and intense seafood-like taste associated with the presence of high salt and volatiles (hexanal, heptanal, nonanal, 2,4 heptadienal). The equivalent umami concentration (g MSG/100 g) in these seaweeds was found to be 0.31–1.81, 2.29–3.03, 1.75–3.04, 55.44–74.44, and 13.83–21.05, respectively. *F. vesiculosus* possessed the highest concentration of nucleotides. Skrzypczyk et al. (2019) compared the palatability of endemic Australasian seaweeds with commercially available seaweeds in salad and soup dishes on 9-point Hedonic scale using the following descriptors–appearance, smell, colour, texture, flavour, saltiness, and sweetness. For soup dishes, no significant difference was observed between different seaweeds. Salad from commercial *Sargassum fusiforme* scored the highest, while *Cystophora polycystidea* scored the least. The participants observed that the salad from *Cystophora torulosa* and commercial *S. fusiforme* were tender, held their form, and were crunchy compared to finer string *C. polycystidea* and *Phyllotricha decipiens* salads which were bitter, tough, and possessed stringy mouthfeel. Some of the terms describing seaweed texture are hard, soft, crunchy, crispy, slimy, chewy, tough, tender, elastic, etc. Generally, the fresh seaweeds are tough and chewy in nature, and processing (cooking, drying, roasting) helps in tenderization. The presence of polysaccharides like alginates may impart sliminess to the seaweed (Mouritsen et al., 2019). Vilar et al. (2020) reviewed the volatiles present in four brown and two red seaweed species. They could observe that around 200 volatiles belonging to 13 different classes (hydrocarbons, ketones, aldehydes, alcohols, halogenated compounds, carboxylic acids, esters, furans, sulphur compounds, phenols, amines, pyrazines, pyridines, and others) were present in these six species of seaweed. These specific compounds, their relative intensities, and their interactions contribute towards specific flavour notes of seaweeds. Carboxylic acids are linked to spices, honey and licorice odours, esters to green odour, and amines/pyrazines to the presence of fish, marine, fatty, and seafood odours. The presence of 6-methyl-5-hepten-2-one provides pleasant notes in seaweed. The presence of bromo- or iodo- (halogenated compounds) along with isoprene gives marine, crustacean, green, and sweet aroma to seaweeds. The type and form affect the texture/mouthfeel of seaweed, i.e. dried, roasted, and fried seaweeds may be crispy, crunchy, and crackly (Mouritsen et al., 2019). Texture of seaweeds is described as hard, soft, crunchy, crispy, slimy, chewy, tough, tender, elastic, etc. In Japan, seaweeds are valued for their mouthfeel, and the main descriptors of mouthfeel are *kuchi atari* (palatability, mouthfeel), *shitazawari* (tongue feel), and *hagotae* (crunchiness, tooth resistance).

Because of their inherent sensory qualities, addition of seaweed is expected to affect the sensory properties of the food product. The following section discusses the sensory changes occurring in food upon the supplementation of seaweed. Kumar et al. (2018) demonstrated that the addition of the seaweed *C. racemosa* (sea grapes) powder in semi-sweet biscuits decreased its lightness, redness, and yellowness values. It is worth mentioning that *C. racemosa* is green in colour due to the presence of chlorophyll pigment. The biscuits were evaluated by panellists on 9-point Hedonic rating test using the following attributes: colour, appearance, texture, flavour, and overall acceptability. With increasing concentration of the seaweed, although the biscuit samples remain acceptable, but a significant decrease was noticed in the sensory scores. This restricts the usage of *C. racemosa* at higher levels. Jenifer and Kanjana (2019) were able to add 30% *Ulva lactuca* seaweed for the preparation of the biscuit. The biscuits scored very high (8.6) on a 9-point Hedonic scale. The biscuits prepared by enrichment with *Kappaphycus cottonii* (5–15%) displayed reduced sensory acceptability scores–taste, flavour, appearance, and texture. Enrichment at 5% level was most preferred by the sensory panellists (Lestari & Sulistiyati, 2019). Oh et al. (2020) studied the effect of *Sargassum fulvellum*, *Codium fragile*, *Sargassum fusiforme*, and *Ulva linza* at 5% level in cookie preparation. The colour of cookies changes as per the colour of the seaweed incorporated. The cookies made from *S. fulvellum*, *C. fragile*, and *U. linza* scored very low on flavour due to the presence of a fishy aroma. This effect was further reflected in their acceptability score, wherein the rating varied from 3.37 to 4.37 (dislike–slight to moderate) on a 9-point Hedonic scale. Hall et al. (2012) used a 9-point scale for evaluating the bread on appearance, aroma, taste, texture, after taste, and overall acceptability and observed no significant reduction in acceptability of *Ascophyllum nodosum*–enriched bread up to 4% level of incorporation. The sensory acceptability score for *A. nodosum* bread varied from 5.79 to 5.95 (‘neither like/dislike’ to ‘like slightly’ range). *Ulva* sp. and *Cladophora* sp. biomass (2.5–7.5%) supplemented bread was evaluated on colour, odour, and consistency parameters by ranking test. Although an increase in the colour intensity of bread with increasing levels of a mix consisting of *Ulva* and *Cladophora* (2.5–7.5%) was observed, but the difference in sensory acceptability was non-significant ($p < 0.05$) (Menezes et al., 2015). The seaweed-enriched bread was classified as of regular quality, with an average score of 75. The average score for good, regular, and bad quality bread is 81–100, 61–80, and 31–60, respectively (Menezes et al., 2015). Mamat et al. (2014) observed that the addition of *Kappaphycus alvarezii* seaweed to bread decreased the lightness and increased the yellowness of the crumb. They recommended up to 8% of *K. alvarezii* to replace wheat flour without denigrating the quality of the final product. Komatsuzaki et al. (2019) made breads supplemented with *Kappaphycus*, *Undaria pinnatifida* (Wakame), and *Ulva* sp. *Wakame* and *Ulva*-supplemented bread were liked for their flavour *Kappaphycus* bread scored most in terms of texture because of the grain fineness. The peculiar aroma of *Kappaphycus* seaweed was masked by using garlic as a flavouring agent in bread. Windrayani and Ekantari (2021) noted that the dim sum wrappers prepared by the addition of *C. racemosa* have significantly different colour values (lightness, redness, and yellowness) and decreased gelatinized starch flavour. The intensity and persistence of sea grapes flavour were more than gelatinized flour flavour. The distinct savoury and umami-like seafood flavour from *C. racemosa* (Amin et al., 2021) might have suppressed the gelatinization notes. Amin et al. (2021) noticed flavour compounds like nonanal, hexanal, (E)-2-octenal, and octanoic acid in sea grapes sauce. Cox and Abu-Ghannam (2013) evaluated the breadsticks on a 5-point scale from like extremely to dislike extremely (aroma, appearance, texture, flavour, acceptability, and combination of all these as overall quality) and found that *Himanthalia elongata*–enriched breadsticks were found acceptable to consumers up to 20% level of incorporation; beyond that, the incorporation resulted in a tough and unacceptable product. Further, the taste scores were affected due to the addition of seaweed and reduced from 3.8 (control) to 2.75 (17% seaweed). The overall acceptability score of seaweed-enriched breadsticks (2.80) was significantly ($p < 0.05$) lower than control sample (3.76). Kumoro et al. (2016) conducted sensory evaluation of the noodles on a scale of 1–10 (‘don’t like’ to ‘like a lot’) which observed the light green colour in instant fried noodles upon supplementation. Ten percent substitution of wheat flour by *Kappaphycus cottonii* and the microalgae *Arthrospira platensis* (formerly *Spirulina platensis*) (Cyanobacteria) and *Chlorella vulgaris* (Chlorophyta) was preferred most by panellists. The colour changed to dark green at higher replacement levels, making the noodles less preferred. The same pattern was observed for the flavour score of the noodles, wherein substitution at higher levels bestowed the noodles with a fishy aroma. Generally, seaweed is expected to impart a distinct smell due to the presence of amines and reduce the acceptability of the product (Kumar et al., 2019). Huang and Yang (2019) noticed that *Eucheuma* sp. powder supplementation in the cakes did not decrease the colour and appearance score up to 20% replacement of wheat flour, but the aroma, flavour, and overall acceptability were acceptable up to 10% levels only. The sensory evaluation was done on a 9-point Hedonic scale on following sensory attributes–appearance, colour, odour, flavour, and overall acceptability. At levels of more than 10%, sponge cake acquired an unpleasant smell and taste. Further, addition at higher levels led to higher hardness and lower volume of cakes, which reflected in the sensory scores (Moza & Gujral, 2017). The addition of *Eucheuma* powder at a lower level (7%) in mille crepes cake imparted a bright yellow colour similar to the control (Ningsih & Anggraeni, 2021). The flavour was acceptable up to 14%, although a mild seaweed smell could be detected. Further increasing the concentration led to enhanced fishy seaweed odour, which may make the product undesirable. At the lower level of addition, the texture was similar to the control, but at the 19.6% level, the cake became grainy, which the authors attributed to the higher fibre content in the seaweed. Acceptable product was made by substitution at a 5% level only, with an overall acceptability score of 4.66 on a scale of 5 (Ningsih & Anggraeni, 2021). Mamat et al. (2018) carried out the sensory evaluation of *K. alvarezii* added muffins on 7-point Hedonic scale (‘dislike extremely’ to ‘like extremely’) on colour, aroma, taste, texture, and overall acceptability. *K. alvarezii* incorporation in muffins decreased the sensory acceptability in a concentration-dependent manner. This decrease was presumably due to the presence of a strong fishy odour and the fishy taste of the seaweed. Seaweed’s taste is taken to be synonymous with fishy taste (Moss & McSweeney, 2021). Muffins prepared by addition at 10% level scored least on all the parameters, while muffins with 2% seaweed powder were similar to the control. They proposed that 6% supplementation did not alter the sensory parameters significantly. Further, the acceptance was most dependent on the aroma and taste of the muffin samples. Cian et al. (2014) utilized the services of trained sensory panellists for evaluating the extruded samples on the basis of colour, smell, taste, flavour, and mouth texture (crispness and adherence). The maize extrudate changed from light yellow to dark green upon incorporation with *Pyropia columbina*. Further, an inverse relationship between lightness and yellowness value and *P. columbina* level was observed. This was attributed to the presence of chlorophyll and phycobilin pigment in the seaweed (Cian et al., 2012). The addition level at 3.5% was found to be most acceptable regarding colour, flavour, and mouth texture, and the extrudates were found to be highly crispy. Similarly, Etemadian et al. (2018) performed the sensory evaluation of the corn snacks enriched with extracts obtained from *Sirophysalis trinodis* and *Polycladia myrica* (at 2–4% level) by quantitative descriptive analysis method using following descriptors: odour (corn snack, rancidity, cheddar cheese/whey), crispy, softness, flavour (cheddar cheese/whey, rancidity), bitterness, sweetness, saltiness, and overall acceptability. No significant difference was noticed in control sample and seaweed-enriched samples. This was primarily due to flavour compounds–cheese and whey powder which masked the sharp odour and flavour of the algal extracts (Etemadian et al., 2018) and thus acting as appropriate flavouring agent which could further be utilized in other food systems. The colour of seaweed-enriched snacks did not differ from the control snack sample (Etemadian et al., 2018).

Among the seafood-based products, the Jeon and Choi (2012) exploited the moisture retention ability of seaweeds to formulate seaweed fortified pork patties. The seaweed-fortified pork patties remained organoleptically acceptable, and the addition did not significantly alter the flavour preference and overall acceptance score, even though seaweed flavour was sensed. Choi et al. (2012) manufactured *S. japonica*–supplemented reduced-fat pork patties and conducted the sensory evaluation in terms of colour, flavour, juiciness, tenderness, and overall acceptability on a 10-point scale (‘extremely desirable’ to ‘extremely undesirable’) and found that the concentration of *S. japonica* powder affected the sensorial properties of reduced-fat pork patties. The dark brown colour of *S. japonica* lowered the colour score of the reduced fat product, but no difference was observed in the flavour score. The seaweed-enriched pork patties scored higher on tenderness, juiciness, and overall acceptability than the control. Dietary fibres exert a beneficial effect on the sensory properties of reduced fat products (Bloukas et al., 1997). Cox and Abu-Ghannam (2013) evaluated the sensory acceptability of *H. elongata* supplemented beef patties on 5-point Hedonic scale in terms of aroma, appearance, texture, flavour, and overall acceptability. The patties were accepted readily by the panellists, and 40% of seaweed-enriched patties scored the highest on overall acceptability due to enhancement in texture and mouthfeel. The acceptability score was the lowest for control (3.75) and

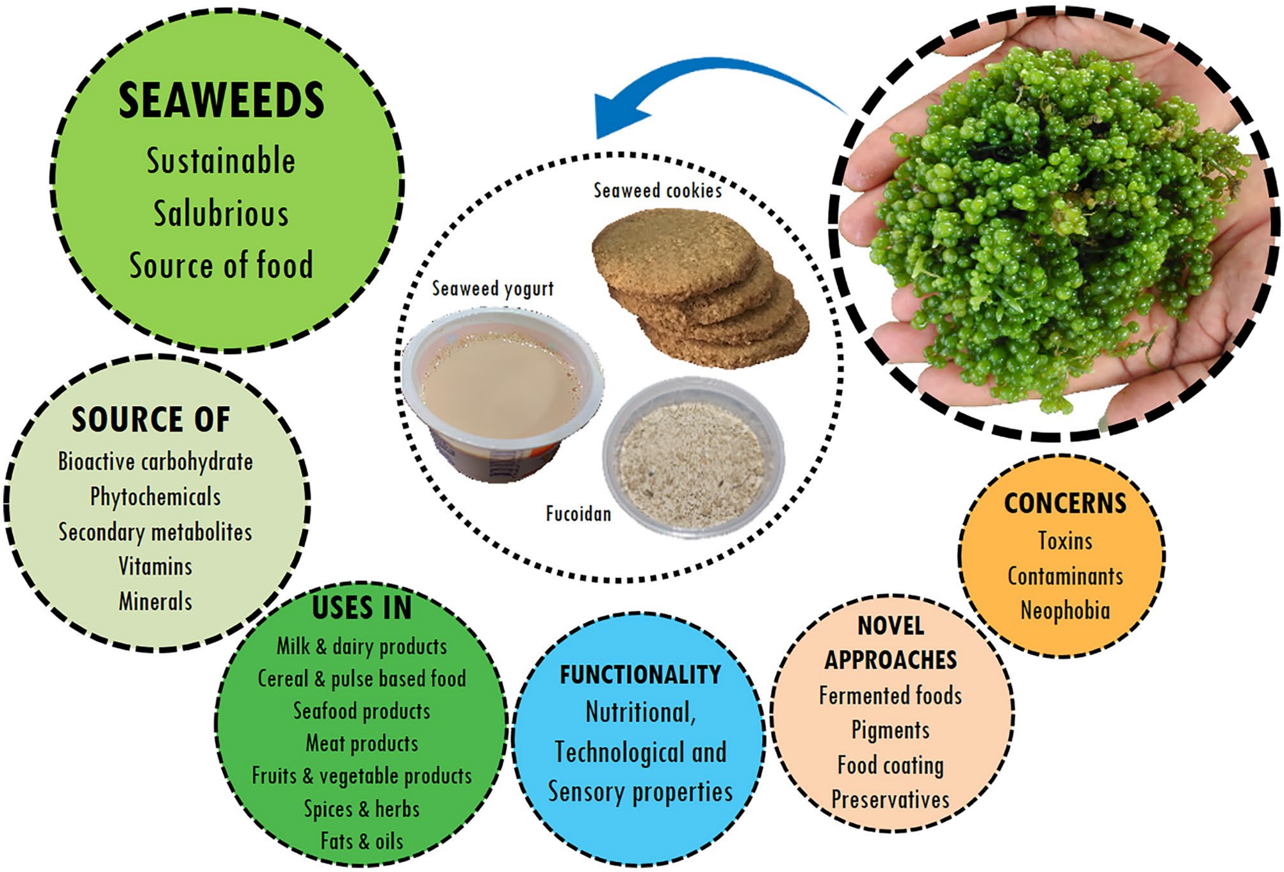

Fig. 1 Seaweed valorization in food systems

the highest for 40% seaweed patties (4.25). Cofrades et al. (2011) noticed that the addition of sea spaghetti powder (*H. elongata*) significantly affected the sensory parameters of the steaks, but the sensory scores were acceptable. The evaluation was carried out in terms of flavour, texture, and overall acceptability using a 10 cm structured scale varying from 0 to 10. The enriched steaks scored very high on flavour and overall acceptability. The sensory panellists were able to identify the seaweed incorporated patties flavour as non-meaty. Jannat-Alipour et al. (2019) evaluated the sensory preference of fish surimi based restructured product in terms of flavour, odour, colour, juiciness, texture, and overall acceptability on 5-point Hedonic scale. The panellists observed that the addition of sulphated polysaccharides gave juicy, tender textured, and lighter-coloured fish surimi restructured product, implying the role of sulphated polysaccharides in moisture retention. The polysaccharide-containing samples were juicier than the control and seaweed-containing samples during frozen storage of 6 months. The overall acceptability was maximum for sulphated polysaccharide-added product and least for seaweed-added product.

Hanjabam et al. (2017) supplemented *S. wightii* powder at 3–5% level in tuna fish jerky and evaluated it in terms of texture, colour, flavour, and overall acceptability. The addition affected the colour, and the product got a brown tone. The product had a spongier and grassy flavour at the 5% addition level, but it scored 7.3 on a 9-point Hedonic scale. At all levels of supplementation, the product remained acceptable.

Okhotnikov et al. (2020) found no reduction in organoleptic qualities in soft cheese at a 0.2% level of addition of kelp. The addition imparted a pleasant greenish colour to cheese. It also made the texture a little dense and the mouthfeel grainy. The smell of the control sample was described as clean sour with bright smell of pasteurization and moderately salty taste. It was weak and creamish in colour and found to be homogenous and moderately dense in consistency. The seaweed-added samples possessed a peculiar smell of kelp and salty-spicy flavour. The cheese samples were denser compared to the control. Hydrated kelp-added cheese was the most dense. Similarly, Dewi and Purnamayati (2021) prepared yoghurt by incorporating the *C. racemosa* seaweed. It was evaluated on 5-point scale for its colour, aroma, texture, and flavour, and the yoghurt was found organoleptically acceptable. The yoghurt was preferred for its colour, aroma, and texture. The yoghurt prepared by adding *Ascophyllum nodosum* and *Fucus vesiculosus* extracts altered the colour of the yoghurt, presumably due to the inherent colour of the extracts. The aqueous extracts were preferred more sensorially than the ethanolic extracts (O'sullivan et al., 2016). Similarly, O'Sullivan et al. (2014) observed the same phenomenon in aqueous and ethanolic extract-enriched milk samples. Kumar et al. (2019) found that the seaweed-coffee samples (*S. wightii*) were satisfactory. One percent seaweed-infused coffee scored the highest for acceptability, just below the control sample. The supplementation of brown seaweed in coffee beverage also decreased the lightness value (L*) and increased the redness (a*) and yellowness value (b*), due to inherent pigment.

Novel and Advance Approaches for Seaweed Utilization

Most of the research is focused on the supplementation of seaweed in bakery products, meat and seafood products, and dairy products. Information regarding seaweed inclusion in fermented foods, edible coatings, preservative, and colouring agents is less and thus presents great opportunity that can be tapped for optimal utilization. Seaweeds are potential substrates for bioconversion through the fermentation process. Fermentation has been practised since ancient times as a means to create new drugs, preserve food, and enhance bioavailability (McGovern et al., 2017). The functional enhancement and bioactivity in fermented food seaweed are attributed to microbial-aided hydrolysis and the release of intracellular compounds (Hur et al., 2014). These intracellular compounds are phenols, phlorotannins, bioactive peptides, sulphated polysaccharides, pigments, and carotenoids. In addition, the microbes involved in the fermentation releases bioactive metabolites such as folates, γ-aminobutyric acid, antimicrobial peptides, bioactive aglycones, depolymerized phenolics, and antioxidant enzymes. During fermentations of seaweeds, polysaccharides, namely alginate, fucoidan, and laminarin, were released from brown seaweeds and are used in biomedical, food, and medicine as active ingredient (Reboleira et al., 2021). There are various species that produce bioactive polysaccharides, and some of their more notable bioactivities include antitumoral, anti-inflammatory, and anticoagulant (Michalak & Chojnacka, 2015). These activities have been associated with sulphated polysaccharides, such as galactans, fucans, heteropolysaccharides, and xyloarabinogalactans (Rodríguez-Jasso et al., 2013). On fermentation of edible red seaweeds, namely, *Sargassum fusiforme* (Phaeophyceae), *Pyropia* sp. *Chondrus ocellatus*, *Gloiopeltis furcata*, *Chondrus elatus* (Rhodophyta), and *Eisenia bicyclis* (Phaeophyceae) using *Lactobacillus plantarum*, a significant rise in the antioxidant activity was recorded illustrating their potential for usage as novel functional foods (Takei et al., 2017). Novel food development by fermenting *Macrocystis pyrifera*, a giant kelp using marine fungi *Paradendryphiella salina*, showed a high functional amino acid content with enhanced antioxidant potential (Salgado et al., 2021). Skonberg et al. (2021) utilized lactic acid fermentation for producing sugar kelp (*Saccharina latissima*) and winged kelp (*Alaria esculenta*) (at 25–75% shredded kelp) fortified sauerkraut. It was noticed that at higher supplementation levels, kelp decreased the fermentation rate and concentration of fermentable sugars in the brine but increased phenolic and antioxidant status. The product quality varied according to the type of kelp utilized for sauerkraut production. Winged kelp sauerkraut was crispier and more greenish compared to sugar kelp sauerkraut. The consumer acceptability of different yoghurts did not differ significantly. The workers further recommended lactic acid fermentation as good option for shelf-life extension and value addition. Protein-rich seaweeds, like *Porphyra* sp., *Gracilaria* sp., and *Ulva* sp., have great potential for the development of new foods and nutraceutical products by utilizing proteolytic microbial strains (Øverland et al., 2019). Protein contents in seaweeds can vary from 10 to 40% (w/w, dry wt.) depending on species and time of harvesting (Pangestuti & Kim, 2015). The food industry has long been interested in the amino acid profile of seaweed protein since the majority of seaweed proteins contain almost all essential amino acids. Seaweeds, particularly brown species, have gained popularity as a protein source in the human diet due to their rich amino acids profile, containing a high percentage of alanine, leucine, threonine, glycine, lysine, and valine and other amino acids like methionine, cysteine, tryptophan, histidine, and tyrosine, present with a comparatively lower percentage (Holdt & Kraan, 2011). In addition, brown seaweeds are rich source of glutamic acids and aspartic acid comprising 44% of the total concentration of amino acids. (Mæhre et al., 2014). The potential for certain peptides to function as ingredients for novel foods has been made clearer by new information about the reactivity and pace of Amadori rearrangements of such peptides (Van Lancker et al., 2011). It has been observed that the fermentation of seaweed protein increases the bioavailability of peptides derived from *Pyropia columbina*, as evidenced by higher antioxidant properties recorded after in vitro simulated gastrointestinal digestion (Cian et al., 2015). Commercial fermented seaweed peptides are already available in Japan in the name of 'Wakame peptide jelly' and 'Nori peptide S' manufactured by the Riken Vitamin Co., Ltd. and the Shirako Co., Ltd. (Nakai et al., 2011). Therefore, bulk manufacture of bioactive peptides from seaweed fermentation has immense possibilities for the creation of new foods (Hou et al., 2015).

Uchida et al. (2017, 2018) reported fermentation of the red seaweed *Neopyropia yezoensis* using *Tetragenococcus halophilus* (bacteria) as starter culture for development of seaweed sauce. The sauce was found to have similar flavour profile with that of commercial soy sauce, and furthermore, the sauce has high umami flavour due to high glutamic, aspartic acid, and taurine content. A fermented seaweed beverage from *Gracilaria fisheri* was reported by Prachyakij et al. (2008) which was developed using a probiotic bacterium *Lactobacillus plantarum.* The product had satisfactory sensory appeal and was stable for 3 months. Norakma et al. (2022) studied aqueous extracts of *Kappaphycus striatum* fermented with kōji mold (*Aspergillus oryzae*). The results revealed a nutritious, functional, and organoleptic appealing product with satisfactory histidine, glutamic acid, and tyrosine concentration of 0.44, 4.27, and 0.64 g/100 g, respectively. Permatasari et al. (2021) studied fermented seaweed beverage prepared with *Caulerpa racemosa* using symbiotic culture of bacteria and yeast (SCOBY), a probiotic tea called 'Kombucha'. The authors reported that the beverage has capacity to lower total cholesterol and blood glucose in animal model, illustrating seaweed Kombucha as the potential anti-ageing functional food. Mun et al. (2017) observed the remarkable suppression of cytokine production by aqueous extract derived from fermented *Sargassum thunbergii.* The fermentation was done using *Lactobacillus* sp. The cytokine is a pro-inflammatory agent, and its suppression indicated anti-inflammatory potential of the extract. According to Bruhn et al. (2019), a fermented seaweed product from *Saccharina latissima* has a milder flavour, enhanced visual and olfactory appeal, and reduced concentration of hazardous trace metals. The texture and protein content of *S. latissima* remained unchanged, but the combined effect of heat treatment (95 °C for 15 min) and fermentation resulted in decreased saltiness, less umami flavour, less slimy appearance, and a reduced seawater smell. Further, the fermentation process minimized the levels of sodium, cadmium, and mercury in *S. latissima* by 15%, 35%, and 37%, respectively. Ko et al. (2014) studied the effect of *kimchi*, a fermented seaweed product from *S. japonica*, and reported the promotion of growth and survival of gut microbial flora LAB in humans. According to Ramnani et al. (2012) most low molecular weight seaweed polysaccharides and oligosaccharides are highly fermentable and have the potential to be prebiotics. *Gelidium* sp. has been observed to have prebiotic potential. Thus, new research and entrepreneurial endeavours can easily take advantage of the production of innovative food products via utilization of seaweeds in fermented foods.

Edible films and coatings enhance quality and shelf life of food due to protective barrier against physico-mechanical damage and semipermeable barrier against gases and water vapour (Peltzer et al., 2017). Seaweeds has been identified as promising environment-friendly alternatives for the mass production of biopolymers that can be used as functional and bio-degradable food packaging material (Tavassoli-Kafrani et al., 2016). The present use of seaweed edible film in the food sector is as sachets, pouches, and wrappers for chocolate and seasoning cubes; as an interleaf for frozen foods; and as a material for edible logos in bakery products. Studies showed that edible films manufactured from the seaweeds polysaccharides derived from *Acanthophora spicifera*, *Ulva lactuca* (as *Ulva fasciata)*, and *Kappaphycus alvarezii* were biocompatible, easily biodegradable, and exhibit satisfactory strength and low deformation (Doh, 2020). Active edible films developed from seaweeds (*Himanthalia elongata* and *Palmaria palmata*) showed high total phenols and antioxidant characteristics which have significant stabilizing effect on pH and water activity in addition to reduction of lipid oxidation and microbial growth in rainbow trout burger over storage (Albertos et al., 2019). Multiple studies have been undertaken to explore the potential of seaweed extracts in improving food preservation and storage. Babakhani et al. (2016) studied peroxide value (PV), volatiles, tocopherol, and sensory quality of chilled (5° C) minced mackerel and reported that additions of the 50% ethanolic extracts of *Vertebrata fucoides* (formerly *Polysiphonia fucoides*) at 0.5 g/kg gave the best protection against lipid oxidation and was just as effective as the synthetic antioxidant BHT. Natural food colours come in a wide colour range and are non-synthetic and safe. Red seaweeds contain phycobiliproteins pigments such as R-phycoerythrin (R-PE, red pigment), R-phycocyanin (blue pigment), and R-allophycocyanin (light-blue pigment) (Galland-Irmouli et al., 1999). But, the use of R-PE as a food colourant is not yet authorized in Europe, while R-PE extracted from *Porphyra* sp. (nori) is being used in Asia as a food colourant (Fleurence et al., 2012). However, France has approved the aqueous extract of C-phycocyanin, a different phycobiliprotein isolated from *Spirulina* species, for use in food applications. This pigment is also reported to be utilized as a food colourant in Japan for some of the food items like candy, ice cream, and beverages (Fleurence, 2016). Other seaweed pigments utilized as bioactive or food colourants in functional foods include chlorophyll, carotenoids like β-carotene, and xanthophylls such as antheraxanthin, zeaxanthin, fucoxanthin, lutein, violaxanthin, and neoxanthin (Manivasagan et al., 2018). According to Pangestuti and Siahaan (2018), the application of seaweed pigments as colourant in food and beverages has added advantages of antioxidant food additive (fucoxanthin), nutraceuticals, and functional ingredients (zeaxanthin, β-Carotene, lutein). Some of these seaweed pigments are reported to be anti-diabetic and anti-obesity through repression of insulin levels and adipose tissue, regulate hyperglycaemia and blood pressure, and lower the risk of cardiac arrest (Déléris et al., 2016). Namvar et al. (2014) and Brown et al. (2014) had also reported anticancer properties (fucoxanthin), antioxidant, immune modulatory, antiangiogenic, antimalarial activities, and anti-inflammatory effects (astaxanthin and fucoxanthin) of seaweed pigments. Thus, these studies illustrated that incorporation of seaweed pigments as food additives indeed has multiple additional health benefits along with sensorial appeal of food products.

Further, among traditional approaches for seaweed usage, fruit and vegetable juices and other ready-to-serve/drink beverages could be used as vector for carrying the bioactive components either as an extract or soluble ingredient. Further, typical ready-to-eat fruit and vegetable-based products like jams, jellies, pickles, chutney, and sauce can be easily prepared with seaweeds alone (Kaliaperumal, 2003) or in combination with other fruits and vegetables. As highlighted earlier, the seaweed carries a typical flavour/aroma; the potential to use them as a flavouring and seasoning agent is immense. Seaweeds contain a range of potential flavour components which can be released by mild processing and used to naturally enhance the flavour of food (Jensen et al., 2022) or to add a salty taste. This could be exploited by enriching fats/oil with seaweed-based flavourings since fat plays a vital role as a flavour carrier (Di Cairano et al., 2021). Like herbs and spices, seaweeds could be an essential adjunct to impart flavour and phyto-therapeutics to various dishes and recipes consumed regularly. Due to varying shapes and colours, seaweeds have the potential be utilized for food presentation purposes (garnishing, decoration) to enhance the aesthetic value. Seaweeds can be smoked, marinated, fermented, fried, roasted, or candied for special taste and flavour considerations (Mouritsen et al., 2019).

Concerns and Challenges Associated with Seaweed Utilization

The salubrious nature of seaweeds makes them highly enticing to be explored for human consumption; however, the concerns associated with their intake must not be overlooked.

Shortage of Seaweed

Seaweed aquaculture produces 97% of the global production of seaweed, while wild harvest has a minuscule contribution in the total seaweed production. However, seaweed aquaculture is highly concentrated in particular region, and the cultivation is confined to only five genera of seaweeds, namely *Laminaria*/*Saccharina* (35.4%); *Kappaphycus*/*Eucheuma* (33.5%); *Gracilaria* (10.5%); *Porphyra*/*Pyropia* (8.6%); and *Undaria* (7.4%). Asia is the largest producer of aquaculture seaweed, contributing more than 97% of aquaculture seaweed production (FAO & WHO, 2022). A limited number of aquaculture seaweed genera and highly localised production areas are major challenges for the global seaweed supply chain. Moreover, wild seaweed production between 1990 and 2019 declined by 18%, across all three major types of seaweed classes (FAO & WHO, 2022).

Toxins and Contaminants in Seaweeds

Some of the secondary metabolites found in seaweed are toxic in nature. The direct consumption (raw form) of some species of marine *Caulerpa* (Chlorophyta), *Gracilaria*, *Acanthophora* (Rhodophyta), *Sphaerotrichia, Nemacystus, and Cladosiphon* (Phaeophyceae) has been associated with illness and even death (Cheney, 2016). After the first reported incident of *Caulerpa* toxicity in humans in the 1960s, a detailed investigation found that the toxins metabolites in *Caulerpa* are caulerin, caulerpicin, and caulerpenyne. Caulerpin and caulerpicin are antimicrobial and anti-insecticides, while caulerpenyne has ichthyotoxic and anti-herbivory activity. However, Vidal et al. (1984) demonstrated that caulerpin and caulerpicin are non-toxic in mouse assay following the oral and intra-peritoneal administration. Prostaglandins and polycavernosides present in *Gracilaria* were suspected to be the responsible agents for toxicity. However, later studies (Nagai et al., 1996; Tan et al., 2002; Yotsu-Yamashita et al., 2004) found that the toxicity was due to toxins from epiphytic cyanobacteria present on the surface of the seaweeds, although there is the possibility of the presence of the minor amount of toxins in the seaweed (Cheney, 2016). Seaweed also harbours several other toxin-producing microorganisms such as cholera (Vugia et al., 1997) and dinoflagellate (Parsons et al., 2011). Various phycotoxins associated with seaweeds are depicted in Table 4. It is worth noting that most of the reported cases of seaweed toxicity are after the consumption of fresh unwashed and uncleaned seaweed collected from wild habitats. Thus, it becomes imperative to know the type of seaweed to be consumed. The seaweeds collected must be appropriately cleaned and processed to make them safe for consumption. Scientific studies on processing techniques to remove epiphytes from the seaweed's surface might probably assist in making seaweed a safer food.

Like seafood, seaweeds are also susceptible to microplastic and plastic additives contamination. Microplastics–emerging pollutants of great concern which are less than 5 mm in size–are ubiquitous and persistent in the marine environment (Gutow et al., 2016). Microplastics are known to attach to the seaweed surface. They adsorb microplastics and act as a carrier in the marine food chain (Li et al., 2020). Kibria et al. (2022) have reported that seaweed possesses a high ingestion rate for microplastics. After the degradation of plastics, leached-out plastic additives such as phthalates, and bisphenol A, may be adsorbed by the seaweed. A study based on laboratory investigation found that the brown seaweed, *Fucus vesiculosus*, can adsorb microplastics on its surface from the aquatic environment. The number of adsorbing microplastics correlates with the concentration of microplastics in the seawater. Further study proves that these microplastics get accumulated in the stomach, gut, and faecal matter of marine gastropods (*Littorina littorea*) when fed with this seaweed (Gutow et al., 2016). Although it might seem that since microplastics are only adsorbed on seaweed, then cleaning and washing might eliminate them; but Li et al. (2020) reported microplastic contaminants from processed seaweed products like nori even after steps like washing and

Table 4 Seaweeds and associated phycotoxins

Seaweed	Associated phycotoxins
Caulerpa (*C. taxifolia*, *C. racemosa*, *C. prolifera*, *C. serrulata*, *C. sertularioides*)	Caulerpin, caulerpicin, caulerpenyne
Gracilaria (*G. verrucosa*, *G. coronopifolia*, *G. edulis*, *G. chorda*)	Prostaglandins (E_2, A_2), aplysiatoxin, debromoaplysiatoxin, manauealides, malyngamides, polycavernosides
Acanthophora (*A. spicifera*)	Polycavernoside A
Cladosiphon (C. okamuranus), *Sphaerotrichia divaricata*, *Nemacystus decipiens*	Diethyl peroxides (a, a'-dihydroxy diethyl peroxide)
Digenea simplex, *Chondria armata* *Alsidium helminthocorton*	Kainoids (kainic acid, domoic acid)

Kumar and Sharma (2021); Higa and Kuniyoshi (2000); Cheney (2016)

drying. Microplastics detected from the packed commercial nori prepared from *Neopyropia yezoensis* (formerly *Pyropia yezoensis)* were reported in the range from 0.9 to 3.0 numbers per gram of nori on a dry wet basis. Therefore, research on processing techniques necessary to eliminate the microplastics from seaweeds may be mandated. Another prominent contaminant in seaweeds of health concern is heavy metals. Seaweeds have the highest ability to absorb and accumulate minerals from their surrounding environment to a level much higher than their environment (Spiegel et al., 2013). This physiological activity makes them more susceptible to contamination with toxic heavy metals. Commercial dried seaweed products were found to have varying levels of Al, As, Cd, Cr, Cu, Hg, Mn, Ni, Pb, and Se in a study conducted in South-Eastern China (Chen et al., 2018). *Sargassum* spp. and its fortified fish products were also found to have Hg (Hanjabam et al., 2017). However, the level was lower than the permitted level in the food products. Fresh seaweeds such as *Sargassum* sp. and *Ulva lactuca* contain heavy metals of health concern although in minute quantities (Hanjabam et al., 2015). Additionally, seaweed may also suffer contamination from pesticides, persistent organic pollutants, polychlorinated biphenyls, polyaromatic hydrocarbons, dioxins, per- and polyfluoroalkyl substances, pharmaceutical and personal care products, and other marine food contaminants. The accumulation of these marine food contaminants in the body causes immense toxicities. Since seaweed uptake these contaminants from the water, strict monitoring and surveillance of the surrounding environment should be followed. Further, washing is known to reduce the level of heavy metals in seaweed (da Silva Junior et al., 2023). The soaking/washing processes may be standardized for alleviating the contaminants from seaweed.

Neophobia

Neophobia has emerged as one of the important challenges which could curtail seaweed consumption. Seaweed, although salubrious, is an alien component of the main diet and eating habits (Losada-Lopez et al., 2021. Seaweeds are traditionally consumed only in a few areas of the globe and are primarily underutilized and not commonly devoured. Neophobia is defined as the reluctance in trying out new foods or avoiding new foods. It is one of the significant barriers apart from safety and quality considerations that affect seaweed consumption in the European market (Blikra et al., 2021; Losada-Lopez et al., 2021) and can be a potential reason causing the failure of a new product (Barrena & Sanchez, 2013). The neophobia varies with the type of consumer, i.e. rural/urban, age group, and education level. The chances of neophobic consumers eating seaweed foods are very less (Birch et al., 2019). Palmieri et al. (2020), Al-thawadi (2018), and Chapman et al. (2015) also observed that the neophobic attitude in the consumers affects the seaweed consumption in a negative manner. Birch et al. (2018) conducted a seaweed consumption study in Australia and found that food neophobia restricts consumer preference for seaweeds and one unit increase in the food neophobia scale decreased the chances of eating seaweed foods by 77% in the upcoming year. The seaweed consumption chances increase by 7.6 times when consumers become familiar with seaweed. The seaweed products were found to be accepted by the people possessing high education, having boldness in food choices–neophilia, a propensity to snack and those who associate seaweed consumption with symbolic value (Birch et al., 2019). They observed that the acceptance of seaweed-wrapped sushi and seaweed-based crackers/snacks/soups was higher compared to fresh seaweed and seaweed-based flakes, sprinkles, seaweed-based drinks, jelly, or even sweets. Some of the major reasons for not eating seaweeds as categorized by Birch et al. (2019) are lack of recipes, lack of preparation skills, lack of information on seaweed (appearance, taste, smell, texture, shelf life, storage), food safety issues (microbiological and chemical contamination), and concern regarding allergenicity. Losada-Lopez et al. (2021) measured neophobia on 'food neophobia scale-FNS (1 to 7)' ('I am afraid to eat things I have never had before' to 'I will eat almost anything') and observed that neophobia negatively impacted the consumer's attitude towards seaweed consumption along with associated satisfaction and consumption willingness. Lucas et al. (2019) concluded that seaweed consumption can be enhanced by removing the apprehension in the consumer's mind. The flavour/aroma of seaweed that consumers do not prefer seems to be one of the significant reasons restricting the acceptance of seaweed. The flavour of seaweed has been described as salty, fishy, earthy, and savoury. A study carried out by Moss and McSweeney (2021) in Canada revealed that consumers preferred dried seaweed and bread over other foods. Further, the consumer preferred fish fillets, cheese, and beef burgers over sausages and yoghurts. This implies the possibility of utilizing dried seaweed as healthy snack food. During the same study, the consumers further stated that they would incorporate seaweed into fish, savoury, seasoning, cereal foods, or as a hidden item, wherein the flavour can be masked. The aforementioned factors must be taken into consideration while deliberating on future research involving seaweed utilization as food.

Regulatory Challenges for Seaweed Utilization in Foods

The exploration of seaweed as alternative food source is suggested amid rapid population increase to overcome insufficient agricultural production. However, as already explained in previous section, seaweeds are known to bioaccumulate hazardous heavy metals and various kinds of contaminants. The usage of seaweed as an ingredient in foods is expected to present unique challenges for meeting functional requirements in compliance with the regulatory requirements. The global trade of edible seaweed products is rapidly increasing, but at present, there is no Codex standard that governs the food safety issues in global seaweed trade. Regional and national legislations on food safety hazards in seaweeds are equally inadequate. The Aquaculture Stewardship Council and the Norwegian Seaweed Farms have introduced private standards on seaweed, but such standards do not address food safety issues sufficiently (FAO & WHO, 2022). Iodine and mercury are the two most prominent food safety hazards in seaweeds meant for use as food and feed. The upper limit of iodine intake as per the European Union Scientific Committee on Food is 600 µg/day and 200 µg/day for adults and children, respectively (EFSA, 2014), whereas for mercury, the maximum residue level in algae and prokaryotic organisms is 0.01 mg/kg, as per the European Commission Regulation No. 464/2018 (EU, 2018). Heavy metal and microchemical pollutants may enter food products of animal origin through seaweed containing food. Hence, the EU Directive 2002/32/EC of the European Parliament and the Council prescribes maximum levels of heavy metals and organochlorines in seaweed meant for use as animal feed (EC, 2002). The maximum permissible levels of arsenic, lead, mercury, and cadmium are 2, 10, 0.1, and 1 mg/kg seaweed (containing 12% moisture), while the maximum permissible levels for aldrin, dieldrin, toxaphene, chlordane, DDT, endosulfan, endrin, heptachlor, hexachlorobenzene, and hexachlorocyclohexane are 0.01, 0.01, 0.1, 0.02, 0.05, 0.1, 0.01, 0.01, 0.01, and 0.20 mg/kg seaweed (containing 12% moisture), respectively. However regulatory requirement framework for seaweeds for direct human consumption all over the world is inadequate or ambiguous. The European Commission Regulation (EU) No 231/2012 of 9 March 2012 prescribes the maximum permissible levels of heavy metals in high value food additives. Arsenic (3 mg/kg), lead (2 mg/kg), mercury (1 mg/kg), cadmium (1 mg/kg), and formaldehyde (50 mg/kg) should be monitored (EU, 2012). In India, the Food Safety and Standards (Food Products Standards and Food Additives) Regulation, 2011 mentions regulatory limits for agar, alginates, and carrageenan. For agar and alginate, lead and arsenic content should be no more than 5 and 3 mg/kg, respectively. For carrageenan, regulatory limits of cadmium (1.5 mg/kg), mercury (1 mg/kg), arsenic (3 mg/kg), and lead (5 mg/kg) have been specified. The Food Safety and Standards (Food Products Standards and Food Additives) Regulation, 2011 by FSSAI, India, has placed seaweed along with vegetables, and regulatory requirements for the usage of food additives are similar for both. The various categories mentioned in the regulation are - fresh seaweeds (untreated/ surface treated/ and peeled/ cut/ shredded or minimally processed); processed seaweeds (frozen/ dried/ seaweeds in vinegar, oil, brine, soybean sauce/ canned or bottled or retorted in pouch/ purees and spreads/ pulps and preparations (dessert/ sauces/ candied)/ fermented products/ cooked or fried). For the fresh seaweed category, no food additives are permitted.

Conclusion

Considering adverse climate change impacts and shrinking cultivable land, seaweeds are projected as the food of the future to sustain the ever-growing human population. The seaweed manifesto report (2020, www.seaweedmanifesto.com) of the United Nations (UN) predicted that 0.1% of the ocean might be covered by cultivated seaweed by 2050 for use as food and producing chemicals. Seaweed aquaculture will definitely play a crucial role in attaining sustainable food security through a booming aquatic economy. Figure 1 depicts an outline concerning seaweed utilization in foods. In recent past, a number of studies highlighted the nutritional, techno-functional, and sensorial functionalities of seaweed in food systems. The presence of protein, dietary fibre (soluble and insoluble), carbohydrates, vitamins (A, D, E, K, B-complex, C), essential minerals (Ca, I, Fe, Zn), amino acids (taurine), and various bioactive compounds (terpenes, acetogenins, alkaloids, phlorotannins, alkaloids, phloroglucinol, eckol, dieckol, fucidiphloroethol, catechin, gallic acid, sulphated polysaccharides, sulpholipids) makes seaweed a food resource which can be utilized for combating the burden of malnutrition and lifestyle diseases. Studies report that the supplementation of seaweed has certainly boosted the protein, dietary fibre, mineral content, and antioxidant status of various foods. However, there is a huge knowledge gap regarding in vivo digestion of seaweeds and seaweed products, followed by assimilation and bioavailability of the released nutrients and nutritionals. The interaction of seaweed components with other food constituents may bring out modifications in the bioavailability of the essential nutrients and bioactive agents. The interaction between seaweed and food constituents becomes significant particularly when the food is processed to make it palatable and safe. In this context, the effect of baking, cooking, frying, thermal processing (pasteurization), extrusion, fermentation, conching, cheese ripening, and advanced processing methods (high pressure processing, ultrasonication, pulsed electric field processing etc.) on bioavailability of nutrients and nutritionals in seaweed-fortified food must be studied. Further, there are chances of the formation of additional useful/harmful compounds, which need to be thoroughly investigated. The bioavailability studies/feeding experiments in animal/human models help in better understanding the behaviour of seaweeds in human nutrition. Seaweed incorporation alters the technological behaviour of food. In general, the addition of seaweed in wheat flour changes the handling properties of the dough and batter and thus alters the final product quality, particularly in terms of texture and mouthfeel. Seaweed fortification also changes the absorption (water/fat) characteristics of the flour, gelatinization behaviour, and phase transitions and interferes with gluten protein. In extrusion processing, seaweed–dietary fibre–has its impact on degree of cooking, residence time, energy consumption, and expansion of extrudates. The water-binding capacity of seaweed (hydrocolloid effect of hydrophilic components) is useful for reducing thawing and cooking losses in restructured foods which are stored frozen and thawed and cooked before consumption. The predominant amino acids in seaweeds decide the taste of seaweed. Seaweeds of Phaeophyceae class are sweet/umami, while those from Rhodophyta phylum give umami taste, although exceptions are also commonly found. The major flavour descriptors for seaweeds are sea-like flavour/taste, grassiness, liquorice flavour, marine flavour, and fishy flavour which are due to the presence of a large number of volatiles. The volatile compounds after processing may lose their intensity and display different flavour profiles. Their flavouring potential can be exploited by using them as flavourings and garnishing agents. Further seaweeds are also explored via fermentation for recovery of high-value ingredients and novel food products. The utilization of seaweeds for edible coatings and colouring agents will enhance the aesthetics as well as nutritional potential by natural means. The traditional processing techniques such as surface treatment, minimal processing, drying, seaweeds in vinegar/oil/brine/soybean sauce, and canning may be explored for enhancing palatability. The presence of seaweed toxins, food contaminants, heavy metals, and microplastics are significant barriers that may impede seaweed consumption. Speciation studies for heavy metals may be carried out to find specific chemical form causing toxic effect. Opportunity is there for devising processing methods for the detoxification/removal of toxins/contaminants found in seaweed as well as seaweed aquaculture in contaminant-free zones. Appropriate taste and flavours could be utilized for removing the hesitancy/dislikeness associated with seaweed taste/flavour.

Whole seaweeds should also be researched for consumption. In this context, there is a need for blanching, chilling freezing, and minimal processing operations to enhance the quality, safety, and shelf life. Seaweeds can be utilized in for designing food products having desirable nutritional and organoleptic attributes. The seaweed may contribute to the development of snack foods (snacking) after drying/frying/roasting and blending with appropriate flavouring agents. The studies on flavour components may assist in eliminating undesirable flavour components for better utilization of seaweed for food. The sensory characteristics of the seaweed may be tailored for meeting the consumer's preference. This will avoid neophobia.

With increasing seaweed farming and trade, there is an increasing demand for safety and quality standards for seaweed, based on risk assessment which needs to be urgently addressed. With rising trade, legislation and regulatory issues concerning seaweed safety should be framed. HACCP-like food safety management approaches might be utilized for assessing the risks associated and removing the health concerns of the general masses. Consumers need to be made aware of the seaweeds' nutritional and health virtues and role in environmental benefits. The emphasis should also be given for making seaweed affordable and available. Rather than generalizing seaweeds as one, major seaweeds should be identified based on their impact on human nutrition, viability of making food products and production, and accordingly, the interventions associated should be seaweed-specific. Along the lines, there is a need to identify/develop suitable technologies/seaweed-based novel products with global appeal and make seaweed truly a future food. Then, seaweed might become a remarkable tool for achieving the United Nations Sustainable Development Goal of Zero Hunger and Good Health and Well-Being.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11947-023-03023-2.

Acknowledgements The authors would like to thank the Director, ICAR-CIFT, for providing the necessary facilities to carry out the present work.

Author Contribution Anuj Kumar, Mandakini Devi Hanjabam, Pankaj Kishore, and Devananda Uchoi carried out the literature review, evaluation of literature data, and drafting. CO Mohan, Satyen Kumar Panda, Niladri Sekhar Chatterjee, AA Zynudheen, and CN Ravishankar designed, edited, and reviewed the manuscript.

Funding This work was carried out under Institutional Project no. 1000661044 [P-107/2018(2)].

Data Availability Not applicable.

Declarations

Conflict of Interest The authors declare no competing interests.

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