Food Chemistry 464 (2025) 141720

Contents lists available at ScienceDirect

Food Chemistry

journal homepage: www.elsevier.com/locate/foodchem

Seaweeds and derived bioactive compounds as food alternatives: Current status and future perspective in Africa

Clarisa Naa Shormeh Darko [a,*], Freda Akua Ampiaw [b], Benjamin Agyei-Tuffour [b], Neill Jurgens Goosen [c], Rando Tuvikene [a,*]

[a] School of Natural Sciences and Health, Tallinn University, Narva mnt 29, 10120 Tallinn, Estonia
[b] Department of Materials Science and Engineering, School of Engineering Sciences, University of Ghana, Anne-Jiagge Road, Legon-Accra, Ghana
[c] Department of Chemical Engineering, Stellenbosch University, Private Bag XI, Matieland, Stellenbosch 7602, South Africa

ARTICLE INFO

Keywords:
Bioactive compounds
Biodiversity
Dietary fiber
Functional food
Nutraceutical
Polysaccharide
Seaweeds

ABSTRACT

The urgency for food security and diversification has necessitated extensive exploration of all potential food options. Seaweeds, now considered potential functional foods are widely consumed across Asia and parts of Europe. In Africa, reports on consumption trends and food-related applications are scarce. About only 1% of the annually harvested ~120,000 (fresh weight) tonnes of commercially useful eucheumatoids are utilized locally in the continent's top-producing country, Tanzania. Ultimately, the intensification of current efforts shall promote up-scaling of the seaweed industry. In this review, we have discussed the nutritional profile and nutraceutical potential of commercially viable species, paying attention to consumer safety measures. Also, prospective food-related application of seaweeds based on current international and local African consumption trends is reviewed. The review further addresses factors that hinder consumer acceptance in Africa and the up-scaling of the seaweed industry at large. This review aims to provide some theoretical reference for future developments and application of seaweed as food in Africa.

1. Introduction

Seaweeds are marine-sourced plant-like organisms that are widely distributed in oceans and aquaculture farms across the globe (Msuya et al., 2022; Rogel-Castillo, Latorre-Castañeda, Muñoz-Muñoz, & Agurto-Muñoz, 2023). By far, over 50,000 species of seaweeds have been identified across 132 countries (Froehlich, Afflerbach, Frazier, & Halpern, 2019; Guiry & Guiry, 2024). The seaweed sector is one of the fastest-growing industries, and about 49 countries are actively involved in seaweed farming. Seaweeds in general are highly diversified but are mainly classified as Rhodophyta, Chlorophyta, and Ochrophyta based on their dominant pigmentation (Pereira, Amado, Critchley, Van de Velde, & Ribeiro-Claro, 2009). Their variable chemical composition makes them applicable across several sectors (Shannon & Abu-Ghannam, 2019; Xie et al., 2023). In the food sector, for instance, ~145 species are either used in whole or processed for inclusion in food products (Froehlich et al., 2019; Shannon & Abu-Ghannam, 2019). A higher percentage of this market is centered in Asia, where seaweed has been recognized as a traditional meal for several centuries (Cai, 2021; Pangestuti & Kim, 2015; Zhang et al., 2022). In Europe, the consumption of seaweed as food began in the fifteenth century and has thenceforth been widely accepted in many parts of the region (Fleurence, 2016). Across Africa, the earliest consumption of seaweeds is documented around the 18th century when coastal residents depended on them for iodine supplementation (Amosu, Robertson-Andersson, Maneveldt, Anderson, & Bolton, 2013; Pérez-Lloréns, Critchley, Cornish, & Mouritsen, 2023). Despite the high biodiversity along the African shorelines, very few reports on seaweed consumption in present times are documented from this region (FAO, 2021; January, Naidoo, Kirby-McCullough, & Bauer, 2019; Msuya et al., 2022; Oucif et al., 2020). Currently, approximately 2200 species are identified along the shores of Africa (Msuya et al., 2022). This population comprises over 1400 red seaweeds, ~400 brown seaweeds and ~ 400 green seaweeds (Guiry & Guiry, 2024; Msuya et al., 2022). Although some African countries like the United Republic of Tanzania are actively involved in seaweed farming, limiting factors that are mostly socio-techno-based challenge the up-scaling of the seaweed sector and have consequently delayed their inclusion into mainstream or traditional African diets (Ktari, Chebil

---

* Corresponding authors.
E-mail address: cnsdarko@tlu.ee (C.N.S. Darko).

https://doi.org/10.1016/j.foodchem.2024.141720
Received 4 April 2024; Received in revised form 10 October 2024; Accepted 18 October 2024
Available online 24 October 2024

Ajjabi, De Clerck, Gómez Pinchetti, & Rebours, 2022; Msuya et al., 2022; Oucif et al., 2020).

Nonetheless, the current global demand for food security and diversification necessitates the consideration of all economically viable and safe food alternatives (Sultana et al., 2023). In attaining this goal, the realization of the significant role of edible seaweeds particularly across regions of Africa is key. Based on this, the current review details the potential economically viable seaweeds across Africa and further outlines prospects for their inclusion into local food products. By addressing major constraints that limit the cultivation and consumption of seaweed as food in Africa, this review study would augment the prospects of the seaweed sector in contributing towards regional and global food security. Moreover, information provided herein, would be beneficial to understanding local consumer needs and possibly provide basic guidelines for reinitiating seaweed as food across Africa.

2. Overview and diversity of seaweed in Africa

2.1. Economically viable seaweed species in Africa

The seaweed population of Africa is highly diversified, owing to the different climate zones across the continent (Msuya et al., 2022; Rothman et al., 2017). The climate condition in this part predominantly ranges from the very warm tropical regions near the equator to the semi-arid and cooler areas of the south (January et al., 2019; Msuya et al., 2022). These differences allow the thriving of commercially useful species like *Eucheuma* spp., *Kappaphycus* spp., *Gracilaria* spp., *Gelidium* spp., *Ulva* spp., *Sargassum* spp. and kelps (Bolton, Cyrus, Brand, Joubert, & Macey, 2016; Darko et al., 2024; Msuya et al., 2022; Segbefia, Barnes, Akpalu, & Mensah, 2018; Yaich et al., 2011). Generally, the kelps are rather abundant along the cool waters of South Africa and Namibia whiles the pelagic *Sargassum* spp., are common along the warm waters of West Africa (Ackah-Baidoo, 2013; Darko, Premarathna, et al., 2024; January et al., 2019; Ofori & Rouleau, 2020; Rothman, Anderson, Kandjengo, & Bolton, 2020). Agar-bearing *Gelidium* spp. and *Gracilaria* spp. are also widely available in Northern Africa whereas the carrageenan-bearing *Eucheuma* sp. and *Kappaphycus* spp. are abundantly cultivated in Eastern Africa (Bolton, Oyieke, & Gwada, 2007; Moussa, Hassoun, Salhi, Zbakh, & Riadi, 2018; Msuya et al., 2022). Currently, thirteen African countries as presented in Table 1, are engaged in either commercial or small-scale seaweed production (Msuya et al., 2022). From this list, Tanzania, South Africa, Morocco, and Madagascar are enlisted as top producers on the continent (FAO, 2021). Their total aquaculture share was indicated to be ~144,909 t in 2019 (FAO, 2021). On the global front, however, only Tanzania is included in the list of top ten producers (FAO, 2021; FAO & WHO, 2022; Junning & Giulia, 2021). In promoting the sector across Africa, some countries in past years reinvested and reinitiated measures to purposely support local workforce and economic benefits from overseas exportation (Msuya, 2020; Msuya et al., 2022; Wakibia, Ochiewo, & Bolton, 2011). Over the years, phycologists and aquaculture experts have conducted field works, designed protocols and systems to evaluate the viability of different species of seaweed to support the already existing wild population (Bolton et al., 2016; Msuya et al., 2022; Rothman et al., 2017; Rothman et al., 2020). In present times, majority of the commercially useful species are rather exported overseas for further processing (Msuya & Hurtado, 2017).

Table 1
Seaweed diversity in thirteen African countries and examples of economically viable species.

Regions	Countries	Identified species	Economic viable species	References
Eastern Africa	Tanzania	428	*Eucheuma* spp. *Kappaphycus* spp.	Msuya et al., 2022
	Madagascar	442	*Gelidium madagascariense, E. denticulatum K. striatus*	Mollion, 2020; Vieira et al., 2021
	Kenya	400	*Eucheuma* spp., *Gracilaria* spp., *Gelidium* spp. *Sargassum* spp.	Bolton et al., 2007; Mwalugha, Wakibia, Kenji, & Mwasaru, 2015
	Mozambique	205	*Eucheuma* spp., *Kappaphycus* spp.	Mattio et al., 2016
	Mauritius	435	*Gracilaria* spp., *Sargassum* spp., *Ulva* spp.,	Bekah et al., 2023; Bolton, Bhagooli, & Mattio, 2012
Southern Africa	South Africa	850	*Ecklonia maxima, Laminaria pallida, Gracilaria* spp., *Gelidium pristoides, Pyropia* spp.	Amosu et al., 2013; Rothman et al., 2020
	Namibia	205	*Laminaria pallida, Ulva* spp.	Rahman, Nyambe, & Küpper, 2020; Rothman et al., 2020
Western Africa	Ghana	200	*Sargassum* spp., *Hypnea musciformis, Eucheuma* spp., *Kappaphycus* spp., *Ulva* spp.	Akrong et al., 2021; Segbefia et al., 2018
	Nigeria	79	*Sargassum* spp., *Ulva* spp.	Oyesiku & Egunyomi, 2014; Solarin, Bolaji, Fakayode, & Akinnigbagbe, 2014
	Senegal	400	*Hypnea musciformis, Meristotheca senegalensis*	Msuya et al., 2022
Northern Africa	Algeria	494	*Ulva* spp. *Caulerpa* spp.	Mehiaoui, Nemchi, Bouzaza, Farah, & Bachir-Bouiadjra, 2022
	Morocco	306	*Gelidium corneum, Gracilaria multipartita*	Moussa et al., 2018
	Tunisia	64	*Gracilaria* spp., *Ulva lactuca*	Benhissoune, Boudouresque, & Verlaque, 2002; Msuya et al., 2022

2.2. Current status of seaweed applications across Africa

2.2.1. Application trend across Eastern Africa

In Eastern Africa, about 107,000–176,000 t (fresh weight) of three eucheumatoid species are harvested per year in Tanzania only. Of these huge volumes, only ~1% are internally processed into value-added products for local consumption (Msuya et al., 2022). The major limiting factor for incorporating into mainstream diet is mostly low consumer acceptance. In addressing this, local organizations in Zanzibar implemented initiatives to promote effective cultivation practices and systems to allow the gradual inclusion of seaweeds and constituents into some local products (Msuya et al., 2022, 2014). At present, hydrocolloids are isolated from *Eucheuma* and *Kappaphycus* spp. using very simple techniques for use in local desserts and sweets (Msuya, 2010). The long-term aim of this initiative was to extend the use of seaweed polysaccharides into locally made jam, juices, snacks, sweets, and noodles (Msuya et al., 2014). However, a larger proportion of the harvested biomass is exported to France, Denmark, Spain or USA for further processing by bigger sister companies like Copenhagen Pectin A/S (CP

Kelco) (FAO, 2020; Msuya, 2010; Msuya et al., 2022).

In Kenya, the consumption trend is largely focused within the aqua and agriculture sectors. In parts of the country, protein-rich formulations are popularly extracted to supplement tilapia fingerlings and as bio-fertilizers for terrestrial plants (Arori, Muthumbi, Mutia, & Nyonje, 2019; Opiyo et al., 2018). To fully assess the nutritional profiles of Kenyan sourced species, higher research institutes have commenced research studies to evaluate the chemical constituents of selected species (Muraguri, Wakibia, & Kinyuru, 2016; Mwalugha et al., 2015). These research institutions including Kenya Marine and Fisheries Research Institute (KMFRI) are additionally, actively involved in promoting the involvement of locals while highlighting the potential benefits of seaweeds (Mwirigi & Theuri, 2012; Opiyo et al., 2018). However, no recent reports are currently presented on the progress of these initiatives.

For Madagascar also, there currently are no reports on the consumption of seaweeds by locals (Mollion, 2020). The carrageenan-bearing species like *Kappaphycus alvarezii* and *Kappaphycus striatus* were only introduced from Tanzania in the twentieth century (Msuya et al., 2022). The cultivation of these commercially useful species is spearheaded by two companies, namely Aromesalgues and Naturalg in the Northeast part of the country and Ocean Farmers in the Southwest region (Mollion, 2020). Although about 600 to 1300 t (dry weight) are harvested from local cultivation, they are mostly exported in raw unprocessed forms, to countries outside Africa (Mollion, 2020; Msuya et al., 2022). A recent report by Mollion (2020) indicated this scenario to be partly a result of the early stage of the Madagascan seaweed industry thus the need for experts and stakeholders to promote research and marketing of the valuable bioactive compounds of seaweeds across the region.

2.2.2. *Application trend across Southern Africa*

In the Southern part of Africa, most of the documented trends on seaweed application are reported from South Africa and Namibia (Amosu et al., 2013;Msuya et al., 2022; Rothman et al., 2020). By this, it is evident the seaweed sector is well-recognized in these regions and the offshore cultivation has particularly increased over the years in Namibia (Msuya et al., 2022). In most parts of South Africa, utilized seaweeds are typically sourced from natural stocks (Rothman et al., 2020). In typical coastal communities in the Eastern and Western Cape provinces, *Pyropia* spp. are simply cleaned and dried with no further extensive processing for consumption as snacks (Amosu et al., 2013; Rothman et al., 2020). This flavorful Nori (*Pyropia*) sheets are also widely used as sushi wrappings in local restaurants and key supply chain shops. In addition to these, seaweeds are processed into powdered forms, flakes or shredded for patronage under labeled names such as 'Seaweed Rib Rub' and 'Roasted seaweed Dukkah'. Aside, these direct seaweed consumption trends, a thriving small-scale collection of *Gelidium* species is also reported along the South and the Eastern coasts of South Africa (Rothman et al., 2020). The collected biomass of *Gelidium pristoides* and *Gracilaria* spp. are sorted, air-dried in open fields and exported for agar extraction (Msuya et al., 2022; Rothman et al., 2020). The endemic South African kelp, *Ecklonia maxima*, is also used by local tribesmen in remedying iodine deficiency (Bordoloi & Goosen, 2020; Pérez-Lloréns et al., 2023; Rothman et al., 2020). In the aquaculture sector also, fresh species of *Ulva* and *Laminaria pallida* are used as feeds for abalones and their constituent compounds are further isolated for use in supplementing feeds for dusky kob fishes and catfishes (Bolton et al., 2016; Naidoo, Maneveldt, Ruck, & Bolton, 2006; Rothman et al., 2020). Feed formulations that contain fresh kelps are similarly used in abalone farming, which usually requires large volumes of seawater (Rothman et al., 2020). Also in South Africa, patented brands like Afrikelp ® and Kelpak ® are made exclusively from kelp-based extracts for use as biostimulants in the agricultural sector (Rothman et al., 2020). Although not all of the beach-cast kelps and *Ulva* species are processed into value-added products, the current status of local applications is substantially higher in this part of Africa.

2.2.3. *Application trend across Western Africa*

The West coast of Africa, generally has a relatively small seaweed population as compared to the other shorelines of Africa (Akrong et al., 2021; Amosu et al., 2013). The coastlines of Ghana, although considered one of the most endowed in this region, has very little documented evidence of seaweed consumption by local people (Agyarko, 2017; Akrong et al., 2021; Amosu et al., 2013). Based on oral histories, particularly of local coastal residents, seaweeds in this part are used in traditional medicines for treating goiter and skin diseases. The effectiveness of these home remedies is attributed to the different bioactive compounds and minerals in seaweeds (Pérez-Lloréns et al., 2023). In recent times, several species like *Sargassum* spp., *Padina* spp., *Ulva* spp., and *Hypnea* spp. along the Ghanaian coasts have been studied at a laboratory scale to characterize their mineral, biochemical, and physicochemical composition (Addico & deGraft-Johnson, 2016; Darko, Premarathna, et al., 2024; Rhein-Knudsen, Ale, Ajalloueian, & Meyer, 2017). In the Western region of Ghana, *Eucheumia* and *Kappahycus* species are cultivated on small scales, specifically for hydrocolloid isolation overseas (Agyarko, 2017). Public institutions in collaboration with international partners have however, established initiatives for cost-effective practices and systems to facilitate the isolation of high-value polysaccharides targeted for the food and nutraceutical industries (Darko, Premarathna, et al., 2024; Rhein-Knudsen, Ale, Ajalloueian, Yu, & Meyer, 2017).

In Nigeria, the inclusion of seaweed as human diet is similarly undocumented in literature. Recent literature on seaweeds from this region, reported the biochemical composition of beach-cast seaweeds and their nutritional profiles (Ibraheem, Komolafe, Bawa, & Oluwole, 2017). Although frameworks for isolating polysaccharides like alginate have been established, cognate efforts are required for the establishment of this sector (Ibraheem et al., 2017). However, the use of seaweeds in the agriculture sector across Nigeria is rather well reported (Ibraheem et al., 2017; Oyesiku & Egunyomi, 2014). Both fresh and dried forms of species of *Ulva* and the pelagic *Sargassum*, are used in supplementing animal feed, and also to enrich bio-fertilizer formulations (Ibraheem et al., 2017; Oyesiku & Egunyomi, 2014). From recent reports in literature, potentially applicable seaweeds for food-related products across Nigeria are listed to be *Gelidium* sp., *Gracilaria* sp., *Ulva* sp., *Sargassum* sp. and *Asparagopsis* sp. (Fakoya et al., 2011). Nonetheless, effective processing systems and techniques are recommended for maximized utilization of these potentially useful species.

2.2.4. *Application trend across Northern Africa*

Across Northern Africa, the application of seaweeds is largely centered around the extraction of polysaccharides from *Gracilaria* and *Gelidium* species, which are either collected locally or imported from other African countries (Amosu et al., 2013; Msuya et al., 2022). In Morocco, commercial scale isolation of agar from *Gelidium* species is by foreign enterprises established in the Northwestern part of the country (Amosu et al., 2013;Kassila et al., 2019; Msuya et al., 2022). Products are, however, commercialized for both local and foreign markets (Kassila et al., 2019). Alginate from invasive species like *Sargassum muticum*is also extracted on a commercial scale (Kassila et al., 2019; Msuya et al., 2022). However, large volumes of both wild and cultivated biomasses of *Gracilaria* spp., *Gelidium* spp. as well as *Laminaria* spp. are still exported overseas (Kassila et al., 2019; Msuya et al., 2022).

In Tunisia, the seaweed processing industry is solely based on carrageenan production. Species like *K. alvarezii* and *E. denticulatum* are usually imported by established companies for processing (Msuya et al., 2022). Along the Algerian coasts and the Mediterranean basin, different species of green seaweeds, like *Caulerpa* spp. have remained prevalent in the past two decades (Mehiaoui et al., 2022; Oucif et al., 2020). However, there has been no report on their local application for feeding or nutraceutical purposes (Oucif et al., 2020). Interested stakeholders across Northern Africa, have recently commenced extensive biochemical studies and assessments for potential developments to maximize the usage of *Asparagopsis taxiformis*, *Padina pavonica*, *Ulva lactuca* and

Cystoseira spp. which grow abundantly along the Mediterranean Sea (Ktari et al., 2022; Oucif et al., 2020; Yaich et al., 2011; Yaich et al., 2013). Overall, the local consumption of seaweed as human food is similarly low in this part of the continent.

Although the food-based application of seaweed is rather lagging across the African regions, developments to market and promote a conscious consumer-driven market are similarly not in the best of state. The realization of a strong seaweed-based food market in this regard would require a multidisciplinary approach and by so, the production of innovative food products for various local food markets on the African continent.

3. Nutritional composition and benefits of consuming seaweeds

3.1. Chemical composition of seaweeds

Many edible seaweeds, are regarded to be naturally nutritious and have since been consumed by local communities worldwide (Padam & Chye, 2020; Shannon & Abu-Ghannam, 2019; Sultana et al., 2023). They contain relative amounts of carbohydrates, dietary fiber, proteins, minerals, and essential lipids (Dawczynski, Schubert, & Jahreis, 2007; Xie et al., 2023). Their nutritional profiles vary depending on species, spatio-temporal factors, season or time of harvest, and post-harvest conditions (Cofrades, Serdaroğlu, & Jiménez-Colmenero, 2013). These factors as they influence heterogeneity of the structural compositions of seaweeds also imply varying ratios of their respective chemical constituents, thus showing the need for extensive evaluation of their chemical contents (Cofrades et al., 2013).

3.1.1. Major constituents- carbohydrates, proteins and lipids

Seaweeds based on the type and species predominantly contain carbohydrates, which comprise ~15–80% polysaccharides (Cassidy, McSorley, & Allsopp, 2018; Rupérez & Saura-Calixto, 2001; Shannon & Abu-Ghannam, 2019). Their carbohydrate composition is typically different from terrestrial plants (Padam & Chye, 2020). Differences in their carbohydrate composition is mainly dependent on type of seaweed. Carrageenans and agar are ubiquitous to red seaweeds, alginates and fucoidan are contained in brown seaweeds and the ulvans in green seaweeds (Fleurence, 2016; Gupta & Abu-Ghannam, 2011; Nordgård & Draget, 2021; Tuvikene, 2021). Alginate, carrageenans, and agar are “generally regarded as safe substances (GRAS) for human consumption (Garcia-Perez et al., 2023; Pereira et al., 2009). The cellular structures of seaweeds also contain essential amino acids, vitamins, lipids, and aromatic compounds that are usually absent in terrestrial plants (Padam & Chye, 2020; Pangestuti & Kim, 2015; Peñalver et al., 2020). The dietary fiber content in seaweeds, also notably compares to well-known fiber-rich foods (Nishinari & Fang, 2017; Peñalver et al., 2020; Xie et al., 2023). Generally, dietary fibers (DF), are grouped into soluble and insoluble fractions based on their properties and ability to form viscous gels in the presence of water (Cassidy et al., 2018; Peñalver et al., 2020). DF plays a crucial role in gut microbiome activities (Grundy et al., 2016; Peñalver et al., 2020). The total dietary fibers in selected seaweed species as shown in Table 2, are comparatively higher than some fresh vegetables and grains (Dawczynski et al., 2007; MacArtain, Gill, Brooks, Campbell, & Rowland, 2007; Peñalver et al., 2020). In green seaweeds, *Ulva* spp., have up to 40% (dw) soluble dietary fiber content with much higher portion in red seaweeds like *Pyropia* spp. Conversely in brown seaweeds, kelps such as *Laminaria* spp. contain higher ratio of insoluble fibers (27–40%) than soluble DF (Holdt & Kraan, 2011; Rupérez & Saura-Calixto, 2001). Inasmuch as there currently exist no defined analytical systems for quantifying the physiological effect of fibers, it is generally accepted to form a part of a healthy diet (Grundy et al., 2016; Peñalver et al., 2020). The soluble portions are associated with intestinal microbiota activities and their potential in decreasing blood sugar and cholesterol are well reported (Garcia-Perez et al., 2023; Grundy et al., 2016). Insoluble fibers, on the other hand, are known to function as laxatives owing to their non-fermentable nature (Peñalver et al., 2020). The amount of soluble fiber in seaweeds however to an extent, influences the bioavailability of contained proteins (MacArtain et al., 2007). Their protein composition as indicated in Table 2, generally varies up to ~50% dry weight. In red seaweeds, for instance, higher levels are contained in *Pyropia* spp. (24.6–50% dw) but lower amounts in species of the genus *Gracilaria* (Echave et al., 2022). The essential amino acids in some edible seaweeds are mostly also comparable to

Table 2
Nutritional profiles of some commercially exploited seaweed species (per dry weight, %dw) and common whole foods (wet weight).

Seaweed species	African countries	Moisture content (%)	Dietary fiber (%)	Proteins (%)	Fatty acids (%)	References
Gracilaria spp.	Kenya Mauritius Morocco South Africa Tunisia	85.2–96.3	5.5–61.6	5–23	0.4–2.3	Cherry, O'Hara, Magee, McSorley, & Allsopp, 2019; Marinho-Soriano, Fonseca, Carneiro, & Moreira, 2006; Pangestuti & Kim, 2015; Premarathna et al., 2022; Véliz et al., 2023
Pyropia spp.	South Africa	77.5–91	3.8–48.6	24.6–50	0.4–2.1	Cherry et al., 2019; Echave et al., 2022; MacArtain et al., 2007; Marsham, Scott, & Tobin, 2007; Sánchez-Machado et al., 2004; Pangestuti & Kim, 2015
Laminaria spp.	Namibia South Africa	86.1–94	6.2–60.5	3–21	0.8–1.0	Cherry et al., 2019; Fleurence, 2016; MacArtain et al., 2007; Marsham et al., 2007; Sánchez-Machado et al., 2004
Sargassum spp.	Ghana Nigeria	61–96.2	7.7–58.9	4–30.3	0.4–4.5	Darko et al., 2024; Darko, Premarathna, et al., 2024; Echave et al., 2022; Marinho-Soriano et al., 2006; Premarathna et al., 2022
Ulva spp.	Algeria Ghana Namibia Nigeria South Africa Tunisia	79.9–96.6	3.8–81.6	8.8–32	1.4–6.7	Echave et al., 2022; Holdt & Kraan, 2011; Kumar, Ganesan, Suresh, & Bhaskar, 2008; Marsham et al., 2007; Premarathna et al., 2022; Yaich et al., 2013, Yaich et al., 2011; Véliz et al., 2023
Some common vegetables and grains (Based on wet weight, %ww)						
Spinach			1.5	2.3–2.8	0.2–0.6	Murcia, Jiménez-Monreal, Gonzalez, & Martínez-Tomé, 2020; Norziah & Ching, 2000
Cabbages			0.9–2.9	0.2–1.6	0.2	MacArtain et al., 2007; Norziah & Ching, 2000
Carrots			2.6	1.0	0.1	MacArtain et al., 2007; Norziah & Ching, 2000
Rice			1.6–3.2	4.0	0.2–2.9	MacArtain et al., 2007; Muttagi & Ravindra, 2020
Soyabeans			5.5	33.8	18.9	Norziah & Ching, 2000
Reference Intakes (RI) (g)			24	50	70	Food and Drinks Federation, 2014

standardized dietary protein requirements (Echave et al., 2022; Pangestuti & Kim, 2015). The amino acid score for red seaweeds is generally higher and almost similar to some animal-based proteins (Pangestuti & Kim, 2015). The essential amino acids in *Ulva* spp., (~40% of total amino acids) are also on par with protein in soybean (Pangestuti & Kim, 2015; Yaich et al., 2011).

The amount of lipids in seaweeds is generally lower and varies between ~0.1 to 15% of dry weight (Padam & Chye, 2020; Sánchez-Machado, López-Cervantes, Lopez-Hernandez, & Paseiro-Losada, 2004). However, several species contain substantial amounts of fatty acids (FAs) including mono-unsaturated FAs (MUFAs), saturated FAs (SFAs), and polyunsaturated FAs (PUFAs) (Garcia-Perez et al., 2023). Long-chain PUFAs (LC-PUFAs), which are precursors of eicosanoids, associated with the synthesis of beneficial PUFAs are also contained in certain species (Padam & Chye, 2020). From Table 2, it is implied that FAs in seaweeds are comparable to the listed common vegetables, but mostly less than that of soybeans. The PUFAs in seaweeds are typically, omega-3 (n-3) and omega-6 (n-6) lipids, thus making them potential sources of beneficial fatty acids in human diet (Dawczynski et al., 2007; Rocha et al., 2021). For a balanced ratio of these PUFAs, it is recommended to consumed n-3:n-6 in a between 1:3 to 1:5 (Rocha et al., 2021). As far this recommended ratio is concerned, compositional seaweed studies have revealed ratio n-6:n-3 of common species to be usually low, thus elucidating the healthy fatty acid profiles of these species (Garcia-Perez et al., 2023). In cases of unbalanced n-3:n-6 ratio per recommendations, it causes a significant decrease in the concentration of vitamin E which consequently favors lipid peroxidation (MacArtain et al., 2007; Rocha et al., 2021; Xie et al., 2023). The overall FAs profiles are however, distinct for different species or strains (Dawczynski et al., 2007). In addition to these, factors such as water temperature, light exposure and intensity, levels of minerals in seawater, nitrogen compounds, and stages of life, influence the synthesis and profiles of seaweed FAs (Rocha et al., 2021).

3.1.2. Other constituents: minerals, vitamins and carotenoids

Seaweeds, as presented in Table 3 are enriched in vitamins, minerals, and polyphenolic compounds (Holdt & Kraan, 2011;Rizzo et al., 2016; Škrovánková, 2011). The respective amounts of these bioactive compounds are similarly highly variable and differ based on seaweed type, season of harvest, and the level of sunlight exposure, which possibly favors species from the tropical regions of Africa (MacArtain et al., 2007; Peñalver et al., 2020).

In classifying vitamins, they are grouped as water-soluble (B-complex and C) and fat-soluble vitamins (A, D, E and K) depending on their solubility (Xie et al., 2023). The water-soluble B-complex vitamins (B_1, B_2, B_{12}) in seaweeds are in higher amounts than the fat-soluble provitamin A (Bekah et al., 2023; Škrovánková, 2011). Vitamin A in seaweed is commonly found in the β-carotene precursor form (Aryee, Agyei, & Akanbi, 2018; Norziah & Ching, 2000; Škrovánková, 2011). Typical species like *Pyropia* spp., are commonly referred to as repository of vitamins, as they are rich in B_{12} which are rather scarce in fruits and vegetables (MacArtain et al., 2007; Padam & Chye, 2020; Škrovánková, 2011). Based on the recalculated recommended dietary allowances (RDA) by Škrovánková (2011), consuming about 1.5 g of *Pyropia* spp. provides the daily recommended allowance of vitamin B_{12}. Species with such B_{12} composition are possible supplement alternatives particularly for strict vegan and vegetarian meal plans where vitamin B_{12} deficiency cases are prevalent (Rizzo et al., 2016; Škrovánková, 2011). In brown seaweeds however, vitamin C is comparatively higher than B-complex vitamins (Škrovánková, 2011). In kelps as an example, *Laminaria* spp., contain ~0.3 and 0.9 mg/ 100 g (dw) of vitamin B_1, and B_2 respectively, and up to ~91 mg/100 g (dw) for vitamin C (Škrovánková, 2011).

The mineral composition of seaweeds, by virtue of their growing environments and absorption mechanisms, is usually about 10–100 times higher than contained in terrestrial vegetables (Holdt & Kraan, 2011). The mineral compositions of seaweeds (up to ~30% dry weight) are majorly sodium, calcium, magnesium, potassium and iodine (Darko et al., 2022; Holdt & Kraan, 2011; MacArtain et al., 2007; Xie et al., 2023). However, the bioavailability of a mineral depends on the type of formed linkages as well as the digestibility of contained polysaccharide (Jiménez-Escrig, Gómez-Ordóñez, & Rupérez, 2011). These formed linkages usually occur within the cell matrix of seaweeds between the anionic sulfated polysaccharides and counterions that further influence ionic interaction and stability of their polymeric chains (Robal, Truus, Volobujeva, Mellikov, & Tuvikene, 2017). Moreover, since the saltiness and temperature conditions of the sea vary across the globe, it is expected to profile different mineral compositions of seaweeds sourced from different marine bodies (Kumar et al., 2008; Lozano Muñoz & Díaz, 2020). In some red seaweeds as shown in Table 3, seaweeds like *Gracilaria* spp. and *Pyropia* spp. accumulate comparatively lower amounts of minerals than brown seaweeds. In brown seaweeds such as *Laminaria* spp. and *Sargassum* spp., calcium concentration ranges up to ~1005 and 1860 mg/100 g respectively whereas *Pyropia* and *Gracilaria* spp. usually contain about 440 and 650 mg/100 g respectively (Fleurence, 2016; Kumar et al., 2008; MacArtain et al., 2007; Xie et al., 2023). Based on the mineral profiles of seaweeds in general, nutritional studies have proven

Table 3
Summarized vitamins, minerals and trace elements in common seaweed species.

	Vitamins			Minerals (mg/100 g)				References
	A (mg/100 g)	B-complex (μg/ 100 g)	C (mg/ 100 g)	Ca	K	Mg	Fe	
Gracilaria spp.	520–800	12.5	28.5	176–650	24.9–1380	58.5–73.1	15.2–95.6	Kumar et al., 2008; Norziah & Ching, 2000; Ratana-Arporn & Chirapart, 2006; Premarathna et al., 2022
Pyropia spp.	360–45,000	33.8–93.1	831	34.2–440	302.2	108.3	5.2	Kumar et al., 2008; MacArtain et al., 2007; Škrovánková, 2011; Xie et al., 2023
Laminaria spp.	440	31.1	91	364–1005	2013	403	45.6	Kumar et al., 2008; Xie et al., 2023
Sargassum spp.	N/A	18.9	153.8	179.4–1860	129.8	86.4	6.7–128.5	Kumar et al., 2008; Ratana-Arporn & Chirapart, 2006; Premarathna et al., 2022; Škrovánková, 2011
Ulva spp.	56	13.6	41.0–200	140–840	245–1540	31–465	6.0–552	Kumar et al., 2008; MacArtain et al., 2007; Premarathna et al., 2022; Ratana-Arporn & Chirapart, 2006; Škrovánková, 2011; Véliz et al., 2023
Dietary reference intake	360–1650 ^{a}	0.5–2.2^{b*} 0.8–3.2b** 1-5^{b***}	15-100^{c}	1000-1200^{d}	3800-4700^{d}	130-420^{d}	8.0-18^{d}	Lozano Muñoz & Díaz, 2020; Škrovánková, 2011

^{a}ug/day of retinol equivalent (RE), ^{b*} Vitamin B_1(mg/day), ^{b**} Vitamin B_2 (mg/day), ^{b***} Vitamin B_{12} (ug/day), ^{c} mg/day, ^{d} mg/g.
N/A- no available data.

their contribution as whole foods for the prevention of iodine, calcium, and iron deficiencies, thus suggesting their potential for preventing some associated cardiovascular diseases (Lozano Muñoz & Díaz, 2020). Inasmuch as minerals are recommended for the human system, it is advised to avoid prolong and excessive intake of minerals like zinc, in order to avoid associated side effects (Lozano Muñoz & Díaz, 2020).

3.2. Application of seaweed in the food industry

3.2.1. Seaweed as nutritional vegetables

Seaweed as commonly referred to as sea vegetable in some countries, is usually consumed directly as a whole food or used for cooking as a food ingredient (Fleurence, 2016; Padam & Chye, 2020). They can be consumed as freshly salted, flavored, dried, fermented, boiled, defrosted or a combination of the above listed (FAO & WHO, 2022; Sultana et al., 2023). In 2018, directly consumed seaweeds accounted for about 48% of the global seaweed usage whereas 32% was recorded for indirect food applications (FAO & WHO, 2022). A larger fraction of this percentage is concentrated in Asia where several species are considered traditional (Fleurence, 2016; Sultana et al., 2023; Zhang et al., 2022). In most other places as well, consuming seaweed directly usually implies using the dried forms of the blades or whole as snacks, food toppings, in salads or desserts, and for sushi wrappings, Fig. 1 (Fleurence, 2016; Rogel-Castillo et al., 2023; Sultana et al., 2023). In parts of Europe, dried seaweeds are ground into coarse flakes or fine powders into pork frankfurters, beef burgers, to garnish dishes, for seasoning, and to replace or supplement flour for cookies, biscuits, bread, pasta and noodles (Fleurence, 2016; Forster & Radulovich, 2015; Shannon & Abu-Ghannam, 2019). The fresh raw forms are also blended to mix with beverages and juices (Fleurence, 2016; Sultana et al., 2023). In typical domestic settings, seaweed is simply cleansed, dried, chopped, boiled, salted, cooked in soy sauce or blended prior to consumption (Fleurence, 2016). The most common species that are consumed directly or added to food products include *Pyropia* spp., *Palmaria palmata*, *Gracilaria* spp., *Kappaphycus* spp., *Laminaria* spp. and *Undaria pinnatifida*, *Sargassum* spp., and *Ulva* spp. (FAO, 2021; Fleurence, 2016; Forster & Radulovich, 2015; Kumar, Tarafdar, & Badgujar, 2021; Sultana et al., 2023). Interestingly, the increasing popularity of Asian cuisine over the years, has played an influential role on numerous food-based applications of seaweeds. On the Western markets, seaweed-based food products are already available and are classified as "novel foods" according to Regulation (EU) 2015/2283 (Fleurence, 2016). Conversely, the rate of direct human consumption across Africa is comparatively low (Msuya et al., 2022; Oucif et al., 2020). From research studies on the inclusion of seaweed in food products, blanched and dried powders of *Porphyra umbilicalis*, *U. pinnatifida* and *Himanthalia elongata* mixed with beef burgers, patties, and poultry steaks enhance the aroma, texture, appearance and antimicrobial properties of such protein-based meals (Cox & Abu-Ghannam, 2013; López-López et al., 2009; Padam & Chye, 2020). Moreover, the addition of some of these species further enhances the n-3:n-6 polyunsaturated fatty acid profile of products, aside supplementing the levels of calcium, magnesium, and vitamins (López-López et al., 2009). For plant-based meals, powdered form of species like *Eucheuma cotonii* mixed with wheat flour for noodles reportedly increases the fiber, lipids, proteins and mineral composition (Kumoro, Johnny, & Alfilovita, 2016). Also, the addition of dried *Ulva lactuca* and 2.5% of *Laminaria* spp., in baked bread products, results in enhanced product texture and sensory appeal (Cofrades et al., 2013). Considering that most of such useful species are widely available across Africa, prospects for their inclusion into food products remains high. It is conceivable that, reinforcing direct human consumption of edible seaweeds across Africa shall similarly support the food supply chain and promote food diversification on the continent (Forster & Radulovich, 2015). In Sub-Saharan Africa, for instance, high profile seaweeds can be used in soups and sauces in combination with the widely consumed local grain and tuber based delicacies (Ekpa, Palacios-Rojas, Kruseman, Fogliano, & Linnemann, 2019; Shannon & Abu-Ghannam, 2019). In a similar way, herbs and spices which are also well patronized in Africa, can be extended to include selected aromatic species. The gradual acceptance of such natural flavors would moreover, contribute to eradicating health complications associated with artificial food flavors and additives.

3.2.2. Seaweed as processed food products

Seaweeds aside their consumption in the raw unprocessed forms, are also subjected to both simple and complex processes to isolate their contained carbohydrates, proteins or pigments for use in food products

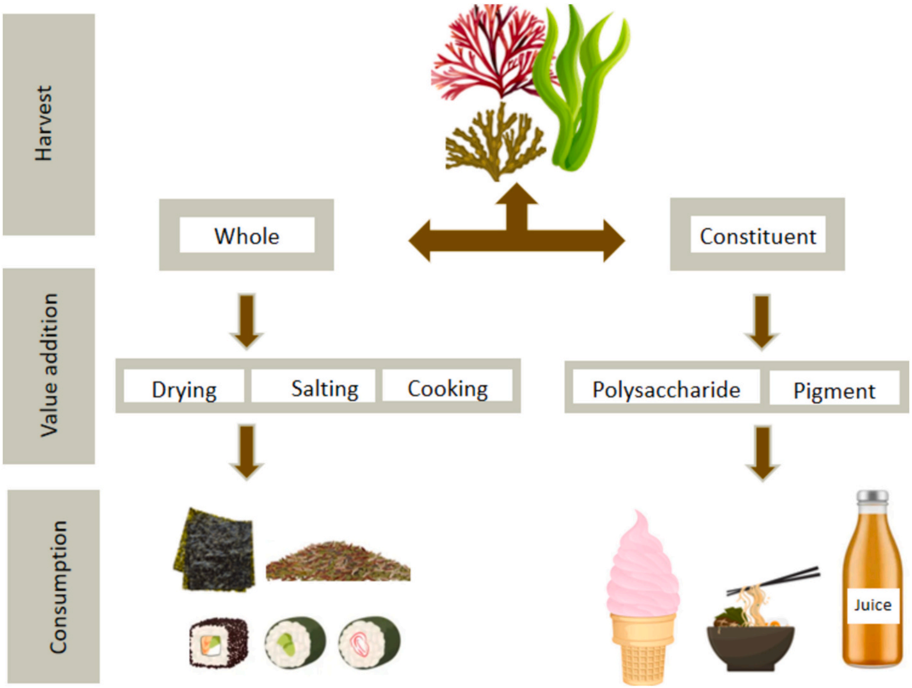

Fig. 1. Some food-related applications of seaweeds and constituent bioactive compounds.

(Cofrades et al., 2013; Fleurence, 2016; Padam & Chye, 2020; Xie et al., 2023). Their applicability however, largely depends on their structural and chemical composition (Aryee et al., 2018; Padam & Chye, 2020). The polysaccharides contained in seaweeds although highly heterogeneous, are normally either sulfated or non-sulfated (Fleurence, 2016; Xie et al., 2023). Their complex structures are made up of forming units called monomers which are connected via glycosidic linkages (You & Sarkar, 2021). Depending on the type of seaweed, the monomeric compositions can be simple sugars (galactose, fucose, rhamnose, xylose, glucose, mannose), sugar alcohols (mannitol) or sugar acids (uronic acids) (Darko, Premarathna, et al., 2024; January et al., 2019; Tuvikene, 2021; Xie et al., 2023). Their chemical constituents including polysaccharides and proteins are extracted using specific solvents and conditions to avoid compromising their structural integrity (Darko, Humayun, et al., 2024; Darko, Premarathna, et al., 2024; January et al., 2019; Nishinari & Fang, 2017; Tuvikene, 2021). The desired sensory appeal, texture and nutritional value of the end product usually determine the choice of seaweed polysaccharide (Venugopal, 2011; Wang et al., 2023). The most common seaweed hydrocolloids widely used in food products are the carrageenans and agar from red seaweeds, and alginate from brown seaweeds (Venugopal, 2011). Hydrocolloids, are generally considered polysaccharides that form gel or highly viscous fluids in water. For this, seaweed sourced hydrocolloids account for about 39% of the total hydrocolloids produced globally (Ellis, Norton, Mills, & Norton, 2017; Venugopal, 2011; Wang et al., 2023). These seaweed hydrocolloids are mostly added into food products to serve as thickeners, stabilizers or gelling agents, Fig. 1 (Tuvikene, 2021). Carrageenans inherent gel-forming ability and are particularly used as additives in Europe under the code E407 (Tuvikene, 2021; Tuvikene et al., 2009). The type of carrageenans obtained specifically from *Kappaphycus* spp. and *Eucheuma* spp. are commonly used as thickeners for barbecue sauces, pet food, jelly desserts, in chocolate and diary toffees, and clarification of wines (Fleurence, 2016; Tuvikene, 2021). Agar which is the main hydrocolloid obtained from *Gracilaria* and *Gelidium* species is known under the code name E406 in the food processing industry across Europe, and is typically used in the baking industry as a binder for pie fillings, icing and glazing (EFSA, 2016; Fleurence, 2016). In Asia, agar-based food products are much popular in Japanese cuisines. It is used as replacement to gelatin in making a traditional sweet red bean paste called '*yōkan*', a jelly dessert called '*mitsumame*' and agar noodles known as '*tokoroten*' (Nishinari & Fang, 2017). For alginate, the sodium form known by the code name E401 is currently used as a gelling agent in syrups, fruit juices, jams, in fillings for apple pies, pet foods, and frozen desserts (Nordgård & Draget, 2021; Williams & Phillips, 2021). Sodium alginate is highly desirable due to the highly viscous nature and good moisture retaining capacity it possesses (Nordgård & Draget, 2021; Wang et al., 2023). In addition to alginates from brown seaweeds, mannitol, is a rather simple sugar alcohol that has recently found usefulness in the food sector (Sultana et al., 2023). The possibilities for incorporating seaweed constituents into conventional food products seem endless and as such extensive studies are ongoing to allow their maximum (Padam & Chye, 2020). In protein-based food systems, carrageenans and alginates are widely resorted to as natural thickeners owing to their favorable protein interaction properties (Williams & Phillips, 2021). Although, hydrocolloids are often used in formulations at concentrations below 1%, they tend to significantly influence stability, texture and flow properties of food products (Williams & Phillips, 2021). In a way to promote the inclusion of seaweed sourced hydrocolloids in African diets, local food industries in liaison with seaweed farmers can establish suitable cost-effective extraction techniques to supplement the conventional thickening agents used for chocolates bars, drinks, porridges and other similar food products. By this, the over-dependence on starch products which are prevalent in Sub-Saharan Africa shall be reduced (Ekpa et al., 2019) Prospects for the African food market will over time increase and fully embrace their use as natural stabilizers, thickeners and texture enhancers.

3.2.3. Seaweed as food colorants

Seaweeds contain pigments that naturally differ based on the seaweed type. These pigments are responsible for the colored appearances of seaweeds and are usually attached to other structural units to form complexes (Aryee et al., 2018; Kumar et al., 2008). Some of these formed complexes based on their purification indexes have been successfully incorporated into food systems as food colors, shown in Fig. 1 (Fleurence, 2016; Saluri et al., 2020). A typical example is phycobiliproteins which is attached to proteins to form pigment-protein complexes (Aryee et al., 2018; Saluri et al., 2020). These phycobiliproteins complexes are water-soluble protein-complexes that are made up of phycoerythrin, phycocyanin and allophycocyanin, which are typically found in red seaweeds (Manivasagan et al., 2018; Pangestuti & Kim, 2015; Saluri et al., 2020). In parts of Asia, R-phycoerythrin is extracted from *Porphyra* for use as food colorants (Fleurence, 2016). Regulations for their full incorporation into food products, however, are not entirely recognized globally. Carotenoids are another common types of pigment complexes contained in certain seaweeds (Pangestuti & Siahaan, 2018). These are mostly yellow, green and orange colored pigments that are also synthesized in plants, certain bacteria, fungi and microalgae in the form of either pure hydrocarbons (carotenes) or oxygenated alcoholic derivatives like xanthophylls, lutein and zeaxanthin (Aryee et al., 2018; Manivasagan et al., 2018). An example of this class of pigment complexes is fucoxanthin, a xanthophyll, which functions as a strong antioxidant agent and is thus very useful for nutraceutical purposes (Aryee et al., 2018; Rajauria, Foley, & Abu-Ghannam, 2017). β-carotene also known to be a precursor of vitamin A is similarly useful in the nutraceutical sector (Aryee et al., 2018; Shannon & Abu-Ghannam, 2019). Consuming β-carotene-rich food product, supplements pro-vitamin A and supports the human immune system (Déléris, Nazih, & Bard, 2016; Manivasagan et al., 2018). Many reports in recent times, have documented interesting health related benefits of seaweed-sourced pigments in general (Manivasagan et al., 2018; Pangestuti & Siahaan, 2018; Rajauria et al., 2017). These reports confer a high-end potential of seaweed pigments in the food and nutraceutical sectors as well their possibilities to serve as natural food colors in-lieu of the widely available synthetic colors and dyes.

3.2.4. Seaweed as animal feed and supplement

Seaweeds and by-product extracts are also commonly used in supplementing feeds for poultry, abalone, cattle, pigs, and aquaculture (Carrillo et al., 2009; Marín et al., 2009; O'Doherty, Dillon, Figat, Callan, & Sweeney, 2010; Roque et al., 2021). Across Europe, there is a long-standing history of feeding ruminants with seaweeds (Fleurence, 2016). In this system of animal farming, cattle, and sheep graze freely on fresh seaweeds at the foreshores or feed on dried seaweeds (Fleurence, 2016; Roque et al., 2021). Pellets and fodder made from kelp species are very common for ruminants and in mixed-up meals for pigs (Fleurence, 2016). From current consumption trends across Africa, a sizable portion of collected seaweeds used to feed farm animals (Oyesiku & Egunyomi, 2014). However, there still remain huge tonnes of beach-cast seaweeds which could be preserved for this purpose and shall subsequently help remediate the existing problems of overgrazing and carbon footprints (Addico & deGraft-Johnson, 2016; Roque et al., 2021). The use of seaweeds like *Asparagopsis* and *Sargassum* spp. in animal silage for steer cows reportedly reduces the enteric methane they produce (Roque et al., 2021). Addition of *Undaria pinnatifida* also enhances cattle growth, improves their immunity, quality of meat and milk, fatty acid profiles of meat and reduces cholesterol concentration (Hwang et al., 2014). In poultry birds, the addition of seaweed extracts rich in carotenoids notably enhances the appearance of eggs (Carrillo et al., 2009; Fleurence, 2016; Xie et al., 2023). In fish farming, inclusion of seaweed-based products supports a healthy growth trend of farmed Atlantic salmons, African catfish, tilapia, *Argyrosomus japonicas* (dusky rob) (Arori et al., 2019; Bolton, Robertson-Andersson, Shuuluka, & Kandjengo, 2009; Rothman et al., 2020). Species like *Ulva* spp., and kelps are commonly used as food for abalones mostly in South Africa (Bolton et al., 2009; Rothman et al., 2020). An additional application in aquaculture, is the consideration for use in high rate algal ponds (HRAPS) (Fleurence, 2016). These systems operate by using seaweeds as food for aquaculture animals, like abalones and mollusks, while simultaneously contributing to the blue economy. This system can be useful in farming high-economic value aquaculture species in the future and some endemic species or blooms can be considered for these purposes.

3.3. *Nutraceutical benefits of consuming seaweeds*

The rich bioactive components of seaweeds make them highly beneficial in the nutraceutical sector (Cofrades et al., 2013; Padam & Chye, 2020; Shannon & Abu-Ghannam, 2019). Their bioactive properties vary from species to species with some examples shown in Fig. 2. Seaweeds are currently proposed to be an alternative nutritional intervention in the alleviation of metabolic syndrome (MetS) or multiple risk factor syndrome (Cherry et al., 2019; Padam & Chye, 2020). Due to the appreciable amounts of dietary fiber, fatty acids, and other metabolites in seaweeds, extensive studies are ongoing on their efficacy against MetS, which are mostly dietary-related disorders and are prevalent worldwide (Murray et al., 2018; Padam & Chye, 2020). In parts of Asia, seaweed as a functional food for alleviating dietary disorders is already well-practiced whereas in Europe, they are best referred to as therapeutic agents, owing to their metabolic composition (Garcia-Perez et al., 2023; Padam & Chye, 2020). Seaweeds for such purposes, are either consumed directly or processed to isolate their metabolites for further applications (Murray et al., 2018; Peng et al., 2018).

3.3.1. *Nutraceutical potential of whole seaweeds*

Some edible seaweeds are commonly consumed as part of daily diet to reduce the occurrence of metabolic diseases such as hyperlipidemia, hypercholesterol and hyperglycemia (Cherry et al., 2019; Yokoyama, Sasaki, & Sato, 2019). *Undaria pinnatifida* (wakame), is a typical example which when consumed, decreases the level of blood glucose and insulin within 30 min of ingestion (Yoshinaga & Mitamura, 2019). This property indicates the potential of such species in regulating postprandial homeostasis (Yokoyama et al., 2019; Yoshinaga & Mitamura, 2019). Some brown seaweeds as well, are shown of playing a role in controlling obesity, postprandial spikes, concentration of serum triglyceride, enhancing lipoprotein cholesterol when added to supplement diets of type-2 diabetic patients (Cassidy et al., 2018; Shannon & Abu-Ghannam, 2019; Yoshinaga & Mitamura, 2019). The overall efficacy of seaweeds in regulating these mechanisms are suggested to be as a result of a synergism between their contained phlorotannins, polyphenols, polysaccharides, fucoxanthin and dietary fiber (Jiménez-Escrig et al., 2011; Murray et al., 2018; Shannon & Abu-Ghannam, 2019). Current reports on the potency of seaweed in remedying food-related disorders seem promising and it is highly recommended for stakeholders of the food sector to actively collaborate and promote the paradigm shift for the nutraceutical application.

3.3.2. *Nutraceutical potential of bioactive compounds from seaweed*

The bioactive compounds in seaweeds, although vary from species to species, present relatively useful dietary intervention pathways (Padam & Chye, 2020). Epidemiological studies on seaweed extracts, either in aqueous or precipitated forms have positive influences on human health (Murray et al., 2018; Peng et al., 2018). Fucoxanthin, a xanthophyll that is typically contained in brown seaweeds is known to possess anti-obesity effects (Padam & Chye, 2020; Rajauria et al., 2017; Shannon & Abu-Ghannam, 2019). A recent study that examined the role of fucoxanthin on consumer health, revealed a significant reduction in

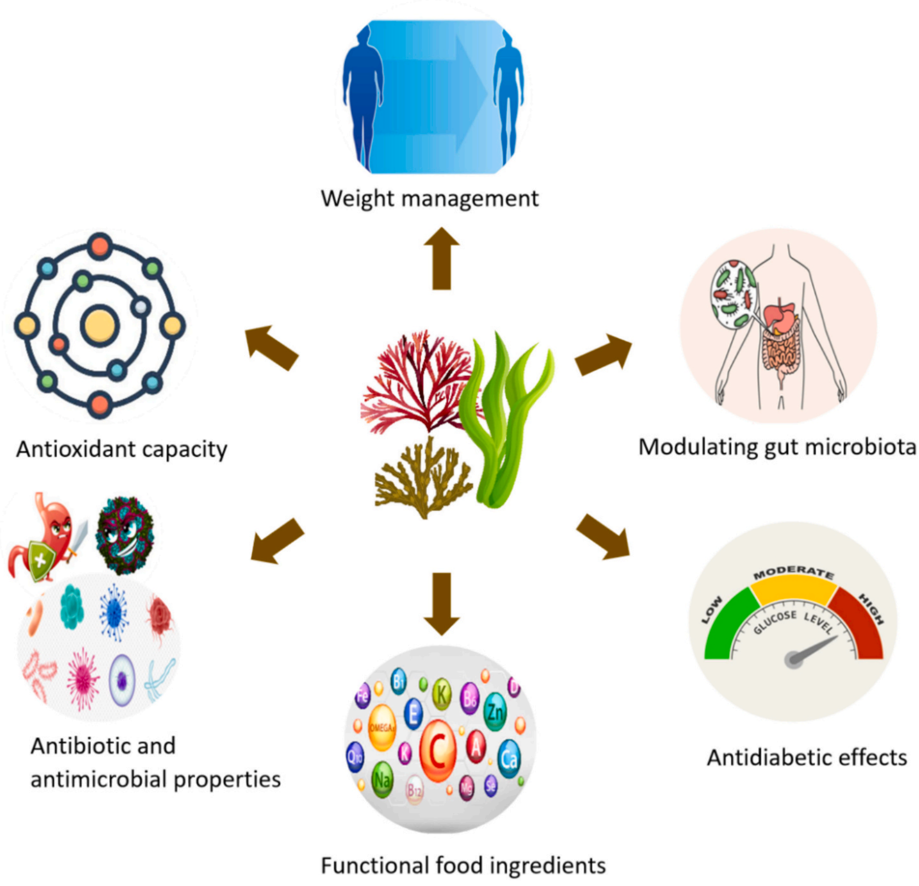

Fig. 2. Functional properties and potential nutraceutical application of seaweeds.

body mass index (BMI), body weight, abdominal fats, and basal metabolic rates occurred upon treatment with 1 mg or 3 mg of fucoxanthin capsules per day for four weeks (Hitoe & Shimoda, 2017). The improvement in consumer health in such applications by seaweed extracts is usually attributed to a combined effect of sulfated polysaccharides and polyphenolic compounds which are mostly co-extracted together (Déléris et al., 2016). In type-2 diabetic patients, dispensing alginate from certain kelp species provides nutritive sugars in a dose dependent manner for hypoglycemia and hyperinsulinemia cases (El Khoury, Goff, Berengut, Kubant, & Anderson, 2014). Related activities from other seaweed polysaccharides are reported on the inhibition of digestive enzymes, α-amylase and α-glycosidase (Cian, Drago, Sanchez de Medina, & Martínez-Augustin, 2015; Darko, Humayun, et al., 2024). These extracted metabolites based on in-vitro studies are able to reduce oxidative cell damage and regulate excessive release of nitric oxide (NO) (Humayun et al., 2024; Premarathna et al., 2024; Humayun et al., 2023). The regulation of excess amounts of NO production subsequently contributes to reducing inflammatory-related diseases like cancer, diabetes and bowel disease (Humayun et al., 2024; Humayun et al., 2023; Tabarsa, You, Dabaghian, & Surayot, 2018). Moreover, these metabolites from seaweeds are highly potent in scavenging free radicals that are very harmful to human cells (Darko, Premarathna, et al., 2024; Humayun et al., 2024; Manivasagan et al., 2018; Shannon & Abu-Ghannam, 2016; Shannon & Abu-Ghannam, 2019). They also are good for use as either prebiotics or carriers of probiotic bacteria for enhancing gastrointestinal digestion (Alvarez, Bambace, Quintana, Gomez-Zavaglia, & del Rosario Moreira, 2021). Both soluble and insoluble fibers are currently under investigation for a more holistic approach to managing microbial imbalance in the human gut (Cian et al., 2015; Jiménez-Escrig et al., 2011). In complex food systems, the desirable synergistic nature of alginates and carrageenans, when mixed with proteins, allows their use as lipid oxidation agents in typical protein-based products like meat and seafood products (Fleurence, 2016; Nordgård & Draget, 2021; Padam & Chye, 2020). Though several scientific researchers have proven the possibilities and potential of bioactive compounds from seaweed as functional food ingredients, additional studies are required to address concerns on precise mechanisms, synergism, and dosages required to manage outlined dietary conditions to promote a healthy consumer lifestyle.

3.4. Challenges and biosafety legislation on seaweed utilization in Africa

3.4.1. Sustainable seaweed production and processing challenges in Africa

The ability of coastal regions along the shorelines of Africa to sustainably produce high profile seaweeds for use across the continent and globe requires strict regulations from farm sites through till the processing factories. Considering the increasing global interest in the seaweed sector and the rich biodiversity of Africa, the upscaling of Africa's seaweed industry would support the global food security and diversification goal (Msuya et al., 2022). Current challenges that limit the realization of this objective are outlined and discussed in subsequent subsections. Respective recommendations to contribute towards addressing these unresolved limitations are also presented.

3.4.2. Cultivation and production challenges

In the period of 2009–2018, only Tanzania was enlisted as part of the top 10 producers out of the 49 countries that dominate the global seaweed sector (FAO, 2020). Records on annual yields of harvested seaweeds show a continuous decline in harvested volumes for most African countries (Msuya, 2020). From the top producers on the continent, only ~0.41% was reported in 2019 (Cai, 2021; FAO & WHO, 2022). This percentage was recorded based on a total of 144,909 t of both wild and farmed seaweeds from Tanzania, Morocco, South Africa and Madagascar (FAO & WHO, 2022). Factors that limit maximized outputs in this sector have been identified by the experts to be mostly techno-economic and biosecurity-based (Msuya et al., 2022). For most regions, persistent infections by the ice-ice syndrome and high volumes of epiphytes have impacted production yields. These pests and diseases mostly hinder the growth of commercially useful seaweed species like *Kappaphycus* (Largo, Msuya, & Menezes, 2020). In an attempt to solve these outbreaks, Tanzania, government, and private stakeholders organize regular training sessions to equip them with the needed combating techniques for the prevention of the spread of pests and diseases (Largo et al., 2020). However, the lack of proper checks on both local and imported seedlings hinders the complete eradication of this problem (Largo et al., 2020; Msuya et al., 2022). In other countries like Madagascar, the outbreak of epiphytes is almost impossible to control and the farmers in these areas, therefore tend to cultivate different species or venture into other businesses (Msuya & Hurtado, 2017). The workforce in seaweed aquaculture in these regions are notably women who are actively engaged in harvesting, sorting, and drying seaweeds (Msuya & Hurtado, 2017). Incentives by stakeholders to support the livelihood of local workers are unfortunately either inadequate or completely absent. One identified challenges that surmounts the topic of species survival, selection of strains, pest and disease control is the absence of rigid biosecurity policies to coordinate these activities of the seaweed farming sector (Msuya et al., 2022). In some regions however, unfavorable climate conditions unfortunately contribute to the challenges associated with selecting the right season for seeding and consequently impact their growth or survival. For these reasons, the farming of certain species is halted during the hot dry seasons, until seasons when temperatures are favorable. All these are important factors that are worthy of deliberation for the provision of effective solutions or alternatives. In remedying these challenges, it is worth initiating an effective management and coordination system that paramount the ease in the livelihood of farmers, technological developments, cost-effective cultivation techniques, value addition, and marketing programs, appropriate gatekeeping systems, and enforcement of biosecurity policies, massive progress will be attained across in the seaweed industry across Africa.

3.4.3. Preservation and storage challenges

In seaweeds, their high moisture usually facilitates oxidation, enzymatic and microbial activities especially when preserved poorly and consequently reduces their shelf life (Cascais et al., 2021). However, the particular preservation technique also influences their final nutritional value (Badmus, Taggart, & Boyd, 2019; Cascais et al., 2021). Although several methods such as blanching, freezing, drying and ensilage have been adapted globally to control this challenge, the scale of production and available structures across Africa, mostly allow the use of open air-drying or direct sun drying (FAO & WHO, 2022). Drying is well known to be an inexpensive technique but due to the uncontrollable nature of drying conditions, nutritional profile and physical quality of seaweeds are usually compromised (Badmus et al., 2019; Cascais et al., 2021). Other available options such as blanching and fermentation are currently practiced in the West but not very common in Africa (Cascais et al., 2021). In solving challenges related to biomass spoilage and decay, it is recommended to consider other cost-effective methods that would preserve the nutritional quality of seaweeds for extended period.

3.4.4. Safety levels of accumulated heavy metals

Seaweeds although several species are confirmed edible, these marine biomasses generally have a good affinity for heavy metals (Besada, Andrade, Schultze, & González, 2009; Fleurence, 2016; Holdt & Kraan, 2011). They can bioaccumulate arsenic, cadmium, copper, lead, mercury, tin, and zinc from their environment contamination (Cherry et al., 2019; Véliz et al., 2023). The level of adoption usually depends on the level of contamination of their habitat and also the bioaccumulation capacity of the seaweed (Bekah et al., 2023; Besada et al., 2009; Cherry et al., 2019). This increases the risk of high levels of heavy metal in perennial seaweeds, that grow or are indirectly exposed to heavy metals (Cherry et al., 2019). Seaweeds harvested from areas close to indiscriminate industrial and domestic discharge sites are much more susceptible to higher bioaccumulation (Addico & deGraft-Johnson, 2016; Besada et al., 2009). In some regions along the coasts of West Africa, this indiscriminate disposal influences higher concentrations of heavy metals in species of *Sargassum* collected along coasts of Ghana (Addico & deGraft-Johnson, 2016). Consuming seaweeds that are highly contaminated with such heavy metals poses severe health risks to humans (Desideri et al., 2016; Gupta & Abu-Ghannam, 2011). For several edible species, however, the bioaccumulation of these harmful metals is usually reported to be below acceptable toxic levels (Besada et al., 2009; Véliz et al., 2023). A prior study to show the accumulation trend of heavy metals revealed that, consuming ~3.3–12.5 g per day of *Laminari*a spp. corresponded to ~40 to 150% of daily cadmium tolerance (Desideri et al., 2016; Zhao, Shang, Ning, & Zhai, 2012). In seaweeds depending on their life stage, and water temperature, they are able to metabolize inorganic arsenic to arsenosugars (Zhao et al., 2012). In selected red, brown and green seaweeds, about 4.1–111.0 μg/g of arsenic were revealed to be arsenosugars with less than 1.0 μg/g inorganic arsenic (Cherry et al., 2019; Taylor & Jackson, 2016). The safety issue of heavy metal accumulation is a global issue that require established guidelines for proper monitoring of water conditions, and safety levels. Some countries have established standards or systems as safety regulations to determine tolerable levels (Holdt & Kraan, 2011; Lozano Muñoz & Díaz, 2020). At present, no document is reported on internalized or local regulations on the tolerable heavy metal levels across Africa.

3.5. Some applicable seaweed preservation methods

3.5.1. Drying

The high moisture content of fresh seaweeds usually facilitates their rapid deterioration when not properly preserved and stored (Badmus et al., 2019; Kadam, Álvarez, Tiwari, & O'Donnell, 2015; Krook et al., 2024). Drying is the easily resorted preservation technique, however, this method also presents a series of challenges that require optimized conditions to be overcome (Badmus et al., 2019; Fudholi, Sopian, Othman, & Ruslan, 2014; Milledge & Harvey, 2016). In optimizing this technique, several modifications have sprouted up over the years. The most common drying methods are solar-drying, oven-drying, and freeze-drying (Badmus et al., 2019; Kadam et al., 2015). Across Africa, open-air drying is the most practiced whereas in other parts of the globe, due to limited hours of sunlight, some farm sites have adapted more towards oven-drying. Oven-drying often demands elevated temperatures for extended durations, which likely interferes with the heat-labile components of seaweeds (Kadam et al., 2015). In Mauritius, the government in collaboration with higher research institutes commenced a pilot scale training and construction of solar dryers (Nazurally et al., 2022). However, no recent updates on the effectiveness of these solar dryers have yet been reported. In the western countries, freeze-drying, despite an expensive system, is shown to be very effective in removing moisture from seaweeds while still preserving the chemical composition of seaweeds (Badmus et al., 2019; Hamid, Wakayama, Soga, & Tomita, 2018). Studies on freeze-dried *Laminaria* spp., *Saccharina japonica* and *Undaria pinnatifida*, showed a preserved profile of seaweed metabolites compared to oven-drying at 40 and 80 °C (Badmus et al., 2019; Hamid et al., 2018). The use of convection dryers at higher temperatures similarly reduces the polyphenolic and flavonoid components in seaweeds (Badmus et al., 2019; Gupta & Abu-Ghannam, 2011). Other non-thermal drying systems like infrared and microwave drying are currently under consideration in some Western countries (Badmus et al., 2019; FAO & WHO, 2022). The intensive energy and labor costs of these techniques limit their upscaling especially for large-scale commercial purposes (FAO & WHO, 2022). Overall, the main identified limitation of drying seaweed is the residual moisture that normally remains after drying. This affects the stability of constituents, possibly as a result of oxidation or microbial activities. In brown seaweeds, for example, the typical residual moisture content is about 5.7–16.2% (Cascais et al., 2021). To overcome this, it is recommended to dry biomass till about 85–90% dryness (Badmus et al., 2019). By far, no single drying method is mentioned to be consistently superior. Different methods remove seaweed moisture better for certain seaweeds than others (Badmus et al., 2019). The implication of this realization is to carefully consider the end-use of seaweeds and select the most suitable drying method accordingly.

3.5.2. Ensilage and fermentation

Ensiling is another preservation method that is gradually gaining popularity in the preservation of seaweed (Cabrita, Maia, Sousa-Pinto, & Fonseca, 2017; Nøkling-Eide et al., 2023). This method also referred to as fermentation commonly involves the introduction of microbial culture or inoculants like *Lactobacillus plantarumor* (LAB) to forage seaweed biomass under anaerobic conditions (Cabrita et al., 2017). This technique has been tested with and without bacteria inoculant and is currently well renown particularly across Europe for the preservation of mostly kelps at extended storage periods (Cabrita et al., 2017; Campbell et al., 2020). Ensiled seaweeds after the intended periods, are used as biomass for polysaccharide extraction and as feed for ruminants. The key limiting factor of this method is the overall heterogeneity of seaweeds which intensely influences activities of the microbial culture (Campbell et al., 2020). However, there is the possibility that different species might be better preserved in the presence of certain culture than others (Cabrita et al., 2017). This present limitation, however, presents a pathway for tailoring specific microbes or enzymes for specific systems soon.

3.5.3. Acid preservation

The use of organic acids like formic, citric, or lactic acids for the preservation of seaweed is fast gaining attention in the seaweed sector, owing to their proven effectiveness (Campbell et al., 2020; Hrólfsdóttir et al., 2024;Krook et al., 2024; Nøkling-Eide et al., 2023). This method specifically uses fresh seaweeds that are either milled or cut into sizable parts and subjected to the process of acidification under anaerobic conditions (Krook et al., 2024; Nøkling-Eide et al., 2023). The process conditions (pH 3 or 4) restrict spoilage by microbial activities (Cabrita et al., 2017; Nøkling-Eide et al., 2023). The simple molecular structures of these naturally occurring organic acids enable their easy mobility into seaweed's cell walls (Theron & Lues, 2007). This method is currently well-investigated across Northern Europe on the fast-deteriorating kelp species (Krook et al., 2024; Nøkling-Eide et al., 2023). For this, organic acids like formic acid (0.1 M) at pH 3.2 are added to milled seaweed samples in anaerobic flasks and stored for periods of up to 16 weeks (Nøkling-Eide et al., 2023). Different concentrations of lactic acid buffered with seawater are also shown to be effective in preserving brown seaweed at different degrees of interest (Krook et al., 2024). Acid preservation, overall, enhances the bioavailability of contained polysaccharides (up to 40%) and cellulose over non-treated samples (Nøkling-Eide et al., 2023). In some cases, lactic acid particularly induces a sour taste in the seaweeds but without compromising their texture (Hrólfsdóttir et al., 2024; Krook et al., 2024). Though the mineral composition of preserved samples, depends on their original content, acidic wash during the process, likely causes partial removal of certain salts (Krook et al., 2024; Nøkling-Eide et al., 2023). Despite these identified limitations, acidification of seaweeds produces no foul smell and is considered to be a cost-effective method for preserving the solid matter of species that contain extremely higher moisture content (Krook et al., 2024; Nøkling-Eide et al., 2023).

3.6. Biosecurity and legislation on consumption safety

Biosecurity as interpreted by the Food and Agriculture Organization (FAO), embodies matters on food safety, zoonosis, management of diseases and pests, introduction of living-modified organisms (LMOs) in biotechnology, and management of invasive alien species (FAO, 2007). To guarantee consumer safety, certain regulations are established to guide the allowed levels of specific undesirable elements in seaweeds (Besada et al., 2009; Desideri et al., 2016; Holdt & Kraan, 2011). Seaweed regulations however, are not entirely universal and the allowed levels vary across regions of the world (Holdt & Kraan, 2011). The allowed levels of toxic heavy metals like mercury, arsenic, lead, and tin are usually critically low, per Food and Drugs Administration laws. Reports from tests on some commercial seaweed products reveal differences in allowed levels across different countries (Besada et al., 2009). In Europe, seaweeds commercialized as food before May 15, 1997, and largely consumed by the populace are accepted on the market and not considered novel foods. However, specific regulations in some European countries restrict the spectrum of edible seaweeds (Holdt & Kraan, 2011). In Africa, existing legislation is largely dependent on international policy frameworks from standard bodies of World Trade Organizations (WTO) and the United Nations (UN) such as the FAO and International Plant Protection Convention (IPPC) for plant biosecurity. These policies are used as basis for the establishment of regional policy frameworks that prioritize standard biosecurity of both terrestrial and marine sourced plants (Campbell et al., 2020; IPPC, 2017; IPPC, 2016). International Sanitary and Phytosanitary Measures (ISPMs) is one of such agreements by the FAO that liaises with relevant international bodies to facilitate and implement biosecurity at both national and regional levels (IPPC, 2016) Nonetheless, no specific generalized legislation is established on the limits of mercury (Hg), cadmium (Cd) and mineral arsenic (As) in seaweed, particularly across Africa. In some parts of Europe, the limits of heavy metals per dry weight in edible seaweeds are indicated as $Pb < 5$ mg/kg, inorganic As <3 mg/kg, $Cd < 0.5$ mg/kg and $Hg < 0.1$ mg/kg (Besada et al., 2009). There is no fixed degree of bioaccumulation of such heavy metals by seaweeds and these are dependent on the pollution levels of cultivation or harvest sites (Bekah et al., 2023; Cherry et al., 2019). This requires the need for strict and intentional evaluation or examination criteria for different collection sites. Additionally, effective region-specific legislations based on expert advice and scientific researchers are well necessitated across regions of Africa.

4. Conclusion

In Africa, several economically viable seaweed species have been identified along the coastal waters. In addition to the huge volumes of wild seaweeds collected annually, the coastlines also offer suitable alternatives for farming specific species. Currently, a large portion of seaweeds harvested from major producers on the continent are exported abroad for processing. Information on local consumption is limited and reports are mostly based on the few available documents, online sources, and preliminary studies. These reports indicate seaweeds across the African continent, are commonly consumed in small proportions as iodine sources, as dried snacks, savory spices, and contained hydrocolloids in sweets, cakes, and jam. Considering the nutritional benefits of seaweeds, it is evident that, the rich seaweed biodiversity of Africa, with evidence-based studies shall contribute to food diversification across the continent. Species of *Pyropia*, *Kappaphycus*, *Gelidium*, *Gracilaria*, *Sargassum and Ulva*, that thrive well across the different regions of Africa could be promoted for the commercialization of seaweed-based food products. Inclusion of seaweeds and related products into local delicacies on the food markets, aside promoting food diversification, also will support the livelihoods of local workers. Some African countries have over the years, implemented both international and regional standard initiatives as guidelines. Other local public and private stakeholders have equally played their parts in ensuring proper seaweed cultivation practices. However, only ~1% of produced seaweeds are used internally for local products. Local governments by this, have presented recommendations that task full participation of government and private stakeholders. In addition, the establishment of well-regulated infrastructures by provision of adequate training, technological developments, research, and processing facilities is recommended for up-scaling the seaweed industry to benefit local markets and further extend to foreign markets.

CRediT authorship contribution statement

Clarisa Naa Shormeh Darko: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Freda Akua Ampiaw:** Writing – review & editing, Investigation. **Benjamin Agyei-Tuffour:** Writing – review & editing, Conceptualization. **Neill Jurgens Goosen:** Writing – review & editing, Validation, Supervision. **Rando Tuvikene:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Acknowledgement

This work was supported by the Estonian Ministry of Foreign Affairs grant TYA21090 and the Estonian Research Council grant PRG1808.

References

Ackah-Baidoo, A. (2013). Fishing in troubled waters: oil production, seaweed and community-level grievances in the Western Region of Ghana. *Community Development Journal, 48*(3), 406–420.

Addico, G. N. D., & deGraft-Johnson, K. A. A. (2016). Preliminary investigation into the chemical composition of the invasive brown seaweed *Sargassum* along the west coast of Ghana. *African Journal of Biotechnology, 15*(39), 2184–2191.

Agyarko, K. A. (2017). Assessing the socio-economic benefits of seaweed production to the rural coastal areas in Ghana. *International Journal of Advances in Science Engineering and Technology, 3*, 32–39.

Akrong, M. O., Anning, A. K., Addico, G. N. D., deGraft-Johnson, K. A. A., Adu-Gyamfi, A., Ale, M., & Meyer, A. S. (2021). Spatio-temporal variations in seaweed diversity and abundance of selected coastal areas in Ghana. *Regional Studies in Marine Science, 44*, Article 101719.

Alvarez, M. V., Bambace, M. F., Quintana, G., Gomez-Zavaglia, A., & del Rosario Moreira, M. (2021). Prebiotic-alginate edible coating on fresh-cut apple as a new carrier for probiotic *lactobacilli* and *bifidobacteria*. *Lwt, 137*, Article 110483.

Amosu, A. O., Robertson-Andersson, D., Maneveldt, G., Anderson, R. J., & Bolton, J. J. (2013). South African seaweed aquaculture: A sustainable development example for other African coastal countries. *African Journal of Agricultural Research, 8*(43), 5260–5271.

Arori, M. K., Muthumbi, A. W. N., Mutia, G. M., & Nyonje, B. (2019). Potential of seaweeds (*Hypnea cornuta* and *Hypnea musciformis*) in Nile tilapia (*Oreochromis niloticus*) fingerlings diets. *International Journal of Fisheries and Aquatic Studies, 7*, 103–107.

Aryee, A. N., Agyei, D., & Akanbi, T. O. (2018). Recovery and utilization of seaweed pigments in food processing. *Current Opinion in Food Science, 19*, 113–119.

Badmus, U. O., Taggart, M. A., & Boyd, K. G. (2019). The effect of different drying methods on certain nutritionally important chemical constituents in edible brown seaweeds. *Journal of Applied Phycology, 31*, 3883–3897.

Bekah, D., Thakoor, A. D., Ramanjooloo, A., Phul, I. C., Botte, S., Roy, P., … Bhaw-Luximon, A. (2023). Vitamins, minerals and heavy metals profiling of seaweeds from Mauritius and Rodrigues for food security. *Journal of Food Composition and Analysis, 115*, Article 104909.

Benhissoune, S., Boudouresque, C. F., & Verlaque, M. (2002). *A checklist of the seaweeds of the Mediterranean and Atlantic coasts of Morocco. II. Phaeophyceae*.

Besada, V., Andrade, J. M., Schultze, F., & González, J. J. (2009). Heavy metals in edible seaweeds commercialised for human consumption. *Journal of Marine Systems, 75*(1–2), 305–313.

Bolton, J. J., Bhagooli, R., & Mattio, L. (2012). The Mauritian seaweed flora: Diversity and potential for sustainable utilisation. *University of Mauritius Research Journal, 18*, 6–27.

Bolton, J. J., Cyrus, M. D., Brand, M. J., Joubert, M., & Macey, B. M. (2016). Why grow *Ulva*? Its potential role in the future of aquaculture. *Perspectives in Phycology, 3*(3), 113–120.

Bolton, J. J., Oyieke, H. A., & Gwada, P. (2007). The seaweeds of Kenya: Checklist, history of seaweed study, coastal environment, and analysis of seaweed diversity and biogeography. *South African Journal of Botany, 73*(1), 76–88.

Bolton, J. J., Robertson-Andersson, D. V., Shuuluka, D., & Kandjengo, L. (2009). Growing *Ulva* (Chlorophyta) in integrated systems as a commercial crop for abalone feed in South Africa: A SWOT analysis. *Journal of Applied Phycology, 21*, 575–583.

Bordoloi, A., & Goosen, N. (2020). Green and integrated processing approaches for the recovery of high -value compounds from brown seaweeds. In *, Vol. 95. Advances in botanical research* (pp. 369–413). Academic Press.

Cabrita, A. R., Maia, M. R., Sousa-Pinto, I., & Fonseca, A. J. (2017). Ensilage of seaweeds from an integrated multi-trophic aquaculture system. *Algal Research, 24*, 290–298.

Cai, J. (2021). *Global status of seaweed production, utilization and trade*. Belize. www.competecaribbean.org/wp-content/uploads/2021/05/Global-status-of-seaweedproduction-trade-and-utilization-Junning-Cai-FAO.pdf.

Campbell, M., Ortuño, J., Ford, L., Davies, D. R., Koidis, A., Walsh, P. J., & Theodoridou, K. (2020). The effect of ensiling on the nutritional composition and fermentation characteristics of brown seaweeds as a ruminant feed ingredient. *Animals, 10*(6), 1019.

Carrillo, S., López, E., Casas, M. M., Avila, E., Castillo, R. M., Carranco, M. E., … Pérez-Gil, F. (2009). Potential use of seaweeds in the laying hen ration to improve the quality of n-3 fatty acid enriched eggs. In *Nineteenth international seaweed symposium: Proceedings of the 19th international seaweed symposium, held in Kobe, Japan, 26-31 March, 2007* (pp. 271–278). Netherlands: Springer.

Cascais, M., Monteiro, P., Pacheco, D., Cotas, J., Pereira, L., Marques, J. C., & Gonçalves, A. M. (2021). Effects of heat treatment processes: Health benefits and risks to the consumer. *Applied Sciences, 11*(18), 8740.

Cassidy, Y. M., McSorley, E. M., & Allsopp, P. J. (2018). Effect of soluble dietary fibre on postprandial blood glucose response and its potential as a functional food ingredient. *Journal of Functional Foods, 46*, 423–439.

Cherry, P., O'Hara, C., Magee, P. J., McSorley, E. M., & Allsopp, P. J. (2019). Risks and benefits of consuming edible seaweeds. *Nutrition Reviews, 77*(5), 307–329.

Cian, R. E., Drago, S. R., Sanchez de Medina, F., & Martínez-Augustin, O. (2015). Proteins and carbohydrates from red seaweeds: Evidence for beneficial effects on gut function and microbiota. *Marine Drugs, 13*(8), 5358–5383.

Cofrades, S., Serdaroğlu, M., & Jiménez-Colmenero, F. (2013). Design of healthier foods and beverages containing whole algae. In *Functional ingredients from algae for foods and nutraceuticals* (pp. 609–633). Woodhead Publishing.

Cox, S., & Abu-Ghannam, N. (2013). Enhancement of the phytochemical and fibre content of beef patties with *Himanthalia elongata* seaweed. *International Journal of Food Science & Technology, 48*(11), 2239–2249.

Darko, C. N. S., Agyei-Tuffour, B., Faloye, D. F., Goosen, N. J., Nyankson, E., & Dodoo-Arhin, D. (2022). Biomethane production from residual algae biomass (*Ecklonia maxima*): Effects of inoculum acclimatization on yield. *Waste and Biomass Valorization, 13*(1), 497–509.

Darko, C. N. S., Humayun, S., Premarathna, A. D., Howlader, M. M., Rjabovs, V., & Tuvikene, R. (2024). Rheology and characterization of sulfated agarans from the edible epiphytic red alga, *Vertebrata lanosa* (truffle seaweed). *Food Hydrocolloids, 151*, Article 109770.

Darko, C. N. S., Premarathna, A. D., Humayun, S., Agyei-Tuffour, B., Goosen, N. J., & Tuvikene, R. (2024). Physico-and biochemical properties of alginates extracted from *Ecklonia maxima* and *Sargassum fluitans* using a simple cascade process. *Journal of Applied Phycology, 36*(2), 661–674.

Dawczynski, C., Schubert, R., & Jahreis, G. (2007). Amino acids, fatty acids, and dietary fibre in edible seaweed products. *Food Chemistry, 103*(3), 891–899.

Déléris, P., Nazih, H., & Bard, J. M. (2016). Seaweeds in human health. *Seaweed in Health and Disease Prevention*, 319–367.

Desideri, D., Cantaluppi, C., Ceccotto, F., Meli, M. A., Roselli, C., & Feduzi, L. (2016). Essential and toxic elements in seaweeds for human consumption. *Journal of Toxicology and Environmental Health, Part A, 79*(3), 112–122.

Echave, J., Otero, P., Garcia-Oliveira, P., Munekata, P. E., Pateiro, M., Lorenzo, J. M., … Prieto, M. A. (2022). Seaweed-derived proteins and peptides: Promising marine bioactives. *Antioxidants, 11*(1), 176.

EFSA Panel on Food Additives. (2016). Re-evaluation of agar (E406) as a food additive. *EFSA Journal, 14*(12).

Ekpa, O., Palacios-Rojas, N., Kruseman, G., Fogliano, V., & Linnemann, A. R. (2019). Sub-Saharan African maize-based foods-processing practices, challenges and opportunities. *Food Reviews International, 35*(7), 609–639.

El Khoury, D., Goff, H. D., Berengut, S., Kubant, R., & Anderson, G. H. (2014). Effect of sodium alginate addition to chocolate milk on glycemia, insulin, appetite and food intake in healthy adult men. *European Journal of Clinical Nutrition, 68*(5), 613–618.

Ellis, A. L., Norton, A. B., Mills, T. B., & Norton, I. T. (2017). Stabilisation of foams by agar gel particles. *Food Hydrocolloids, 73*, 222–228.

Fakoya, K. A., Owodeinde, F. G., Akintola, S. L., Adewolu, M. A., Abass, M. A., & Ndimele, P. E. (2011). An exposition on potential seaweed resources for exploitation, culture and utilization in West Africa: A case study of Nigeria. *Journal of Fisheries and Aquatic Science, 6*(1), 37.

FAO. (2007). Biosecurity toolkit. In *Food and Agriculture Organisation of United Nations* (p. 128). Rome: FAO. https://doi.org/10.1073/pnas.0703993104.

FAO. (2020). *The state of world fisheries and aquaculture 2020*. Rome: Sustainability in action. https://doi.org/10.4060/ca9229e

FAO. (2021). FAO global fishery and aquaculture production statistics – FishStatJ, March 2021. In *FAO Fisheries and Aquaculture. Rome.* fao.org/fishery/statistics/software/fishstatj/en.

FAO and WHO. (2022). *Report of the expert meeting on food safety for seaweed – Current status and future perspectives. Rome, 28–29 October 2021. Food Safety and Quality Series No. 13. Rome.* https://doi.org/10.4060/cc0846en

Fleurence, J. (2016). *Seaweeds as food. Seaweed in health and disease prevention* (pp. 149–167).

Food and Drinks Federation. (2014). *Food and drink labelling: A tool to encourage healthier eating*. Available at https://gdalabel.org.uk/files/corporate_pubs/food_drink_labelling_toolkit.pdf Accessed on August 2023.

Forster, J., & Radulovich, R. (2015). Seaweed and food security. In B. K. Tiwari, & D. J. Troy (Eds.), *Seaweed sustainability - food and non-food applications* (pp. 1–6). Amsterdam: Academic Press. https://doi.org/10.1016/B978-0-12-418697-2.00001-5.

Froehlich, H. E., Afflerbach, J. C., Frazier, M., & Halpern, B. S. (2019). Blue growth potential to mitigate climate change through seaweed offsetting. *Current Biology, 29*(18), 3087–3093. https://doi.org/10.1016/j.cub.2019.07.041

Fudholi, A., Sopian, K., Othman, M. Y., & Ruslan, M. H. (2014). Energy and exergy analyses of solar drying system of red seaweed. *Energy and Buildings, 68*, 121–129.

Garcia-Perez, P., Cassani, L., Garcia-Oliveira, P., Xiao, J., Simal-Gandara, J., Prieto, M. A., & Lucini, L. (2023). Algal nutraceuticals: A perspective on metabolic diversity, current food applications, and prospects in the field of metabolomics. *Food Chemistry, 409*, Article 135295.

Grundy, M. M. L., Edwards, C. H., Mackie, A. R., Gidley, M. J., Butterworth, P. J., & Ellis, P. R. (2016). Re-evaluation of the mechanisms of dietary fibre and implications for macronutrient bioaccessibility, digestion and postprandial metabolism. *British Journal of Nutrition, 116*(5), 816–833.

Guiry, M. D., & Guiry, G. M. (2024). *AlgaeBase. World -wide electronic publication*. University of Galway. https://www.algaebase.org Accessed March, 2024.

Gupta, S., & Abu-Ghannam, N. (2011). Bioactive potential and possible health effects of edible brown seaweeds. *Trends in Food Science & Technology, 22*(6), 315–326.

Hamid, S. S., Wakayama, M., Soga, T., & Tomita, M. (2018). Drying and extraction effects on three edible brown seaweeds for metabolomics. *Journal of Applied Phycology, 30*(6), 3335–3350.

Hitoe, S., & Shimoda, H. (2017). Seaweed fucoxanthin supplementation improves obesity parameters in mild obese Japanese subjects. *Functional Foods in Health and Disease, 7*(4), 246–262.

Holdt, S. L., & Kraan, S. (2011). Bioactive compounds in seaweed: Functional food applications and legislation. *Journal of Applied Phycology, 23*, 543–597.

Hrólfsdóttir, A.P., Arason, S., Sveinsdóttir, H. I., Sæther, M., Aasen, I. M., & Gudjónsdóttir, M. (2024). Physicochemical-and bioactive properties of acid preserved *Alaria esculenta* and *Saccharina latissima* during storage. *LWT, 199*, Article 116109.

Humayun, S., Howlader, M. M., Rjabovs, V., Reile, I., Premarathna, A. D., & Tuvikene, R. (2024). Biological activity of enzymolysed ι-carrageenan of polydisperse nature. *Food Hydrocolloids, 149*, Article 109621.

Humayun, S., Premarathna, A. D., Rjabovs, V., Howlader, M. M., Darko, C. N. S., Mok, I. K., & Tuvikene, R. (2023). Biochemical characteristics and potential biomedical applications of hydrolyzed Carrageenans. *Marine Drugs, 21*(5), 269.

Hwang, J. A., Islam, M. M., Ahmed, S. T., Mun, H. S., Kim, G. M., Kim, Y. J., & Yang, C. J. (2014). Seamustard (*Undaria pinnatifida*) improves growth, immunity, fatty acid profile and reduces cholesterol in Hanwoo steers. *Asian-Australasian Journal of Animal Sciences, 27*(8), 1114.

Ibraheem, O., Komolafe, T. O., Bawa, E., & Oluwole, J. O. (2017). Preliminary evaluation of Nigeria coastal line seaweeds for the alginate content and biochemical constituents Environment & Research. *Journal of Environment and Biotechnology Research, 6*(2), 220–227.

IPPC. (2016). International Standard for Phytosanitary Measures (ISPM) 2- framework for pest risk analysis. *International plant protection convention* (pp. 2–16). Available at: http://www.fao.org/3/a-k0125e.pdf Accessed on 23 August 2024.

IPPC. (2017). Recommendation on: IPPC coverage of aquatic plants. Adopted in 2014. In *International plant protection convention. R04-2017* (pp. 1–2). https://assets.ippc.int/static/media/files/publication/en/2017/08/R_04_En_2017-08-23_Combined_t0E0X8h.pdf Accessed on 23 August 2024.

January, G. G., Naidoo, R. K., Kirby-McCullough, B., & Bauer, R. (2019). Assessing methodologies for fucoidan extraction from south African brown algae. *Algal Research, 40*, Article 101517.

Jiménez-Escrig, A., Gómez-Ordóñez, E., & Rupérez, P. (2011). Seaweed as a source of novel nutraceuticals: Sulfated polysaccharides and peptides. *Advances in Food and Nutrition Research, 64*, 325–337.

Junning, C., & Giulia, G. (2021). *Global seaweeds and microalgae production, 1950–2019*. Rome, Italy: World Aquaculture Performance Indicators (WAPI).

Kadam, S. U., Álvarez, C., Tiwari, B. K., & O'Donnell, C. P. (2015). Processing of seaweeds. In *Seaweed sustainability* (pp. 61–78). Academic Press.

Kassila, J., Nhhala, H., Givernaud, T., Monsouri, M., Yazami, O., Abrehouch, A., … Indahala, M. (2019). Opportunities for the development of seaweed farming as a supplementary income for small-scale fishermen in Nador lagoon: Experimental cultivations of *Gracilaria gracilis* (Stackhouse). *Mediterranean Fisheries and Aquaculture Research, 2*(1), 12–26.

Krook, J. L., Riboldi, L., Birkeland, I. M., Stévant, P., Larsen, W. E., Rhein-Knudsen, N., … Horn, S. J. (2024). Acid preservation of the brown seaweed *Saccharina latissima* for food applications. *Algal Research, 80*, Article 103524.

Ktari, L., Chebil Ajjabi, L., De Clerck, O., Gómez Pinchetti, J. L., & Rebours, C. (2022). Seaweeds as a promising resource for blue economy development in Tunisia: Current state, opportunities, and challenges. *Journal of Applied Phycology*, 1–17.

Kumar, C. S., Ganesan, P., Suresh, P. V., & Bhaskar, N. (2008). Seaweeds as a source of nutritionally beneficial compounds-a review. *Journal of Food Science and Technology, 45*(1), 1.

Kumar, Y., Tarafdar, A., & Badgujar, P. C. (2021). Seaweed as a source of natural antioxidants: Therapeutic activity and food applications. *Journal of Food Quality, 2021*, 1–17.

Kumoro, A. C., Johnny, D., & Alfilovita, D. (2016). Incorporation of microalgae and seaweed in instant fried wheat noodles manufacturing: Nutrition and culinary properties study. *International Food Research Journal, 23*(2).

Largo, D. B., Msuya, F. E., & Menezes, A. (2020). Understanding diseases and control in seaweed farming in Zanzibar. *FAO Fisheries and Aquaculture Technical Paper, 662*, 0_1-49.

López-López, I., Bastida, S., Ruiz-Capillas, C., Bravo, L., Larrea, M. T., Sánchez-Muniz, F., … Jiménez-Colmenero, F. (2009). Composition and antioxidant capacity of low-salt meat emulsion model systems containing edible seaweeds. *Meat Science, 83*(3), 492–498.

Lozano Muñoz, I., & Díaz, N. F. (2020). Minerals in edible seaweed: Health benefits and food safety issues. *Critical Reviews in Food Science and Nutrition, 62*(6), 1592–1607.

MacArtain, P., Gill, C. I., Brooks, M., Campbell, R., & Rowland, I. R. (2007). Nutritional value of edible seaweeds. *Nutrition Reviews, 65*(12), 535–543.

Manivasagan, P., Bharathiraja, S., Santha Moorthy, M., Mondal, S., Seo, H., Dae Lee, K., & Oh, J. (2018). Marine natural pigments as potential sources for therapeutic applications. *Critical Reviews in Biotechnology, 38*(5), 745–761.

Marín, A., Casas-Valdez, M., Carrillo, S., Hernández, H., Monroy, A., Sanginés, L., & Pérez-Gil, F. (2009). The marine algae *Sargassum* spp.(Sargassaceae) as feed for sheep in tropical and subtropical regions. *Revista de Biología Tropical, 57*(4), 1271–1281.

Marinho-Soriano, E., Fonseca, P. C., Carneiro, M. A. A., & Moreira, W. S. C. (2006). Seasonal variation in the chemical composition of two tropical seaweeds. *Bioresource Technology, 97*(18), 2402–2406.

Marsham, S., Scott, G. W., & Tobin, M. L. (2007). Comparison of nutritive chemistry of a range of temperate seaweeds. *Food Chemistry, 100*(4), 1331–1336.

Mattio, L., Zubia, M., Maneveldt, G. W., Anderson, R. J., Bolton, J. J., De Gaillande, C., … Payri, C. E. (2016). Marine flora of the Iles Eparses (Scattered Islands): A longitudinal transect through the Mozambique Channel. *Acta Oecologica, 72*, 33–40.

Mehiaoui, S., Nemchi, F., Bouzaza, Z., Farah, T., & Bachir-Bouiadjra, B. (2022). Algal diversity study in the western Algerian coast. *Ukrainian Journal of Ecology, 12*(5), 1–11.

Milledge, J. J., & Harvey, P. J. (2016). Potential process 'hurdles' in the use of macroalgae as feedstock for biofuel production in the British Isles. *Journal of Chemical Technology & Biotechnology, 91*(8), 2221–2234.

Mollion, J. (2020). The seaweed resources of Madagascar. *Botanica Marina, 63*(1), 97–104.

Moussa, H., Hassoun, M., Salhi, G., Zbakh, H., & Riadi, H. (2018). *Checklist of seaweeds of Al-Hoceima National Park of Morocco (Mediterranean marine protected area)*.

Msuya, F. E. (2010). Development of seaweed cultivation in Tanzania: The role of the University of Dar es Salaam and other institutions. *World Aquaculture, 42*(3), 45–48.

Msuya, F. E. (2020). Seaweed resources of Tanzania: Status, potential species, challenges and development potentials. *Botanica Marina, 63*(4), 371–380.

Msuya, F. E., Bolton, J., Pascal, F., Narrain, K., Nyonje, B., & Cottier-Cook, E. J. (2022). Seaweed farming in Africa: Current status and future potential. *Journal of Applied Phycology, 34*(2), 985–1005.

Msuya, F. E., Buriyo, A., Omar, I., Pascal, B., Narrain, K., Ravina, J. J., … Wakibia, J. G. (2014). Cultivation and utilisation of red seaweeds in the Western Indian Ocean (WIO) region. *Journal of Applied Phycology, 26*, 699–705.

Msuya, F. E., & Hurtado, A. Q. (2017). The role of women in seaweed aquaculture in the Western Indian Ocean and South-East Asia. *European Journal of Phycology, 52*(4), 482–494.

Muraguri, E.N., Wakibia, J.G., & Kinyuru, J.N. (2016). Chemical composition and functional properties of selected seaweeds from the Kenya Coast.

Murcia, M. A., Jiménez-Monreal, A. M., Gonzalez, J., & Martínez-Tomé, M. (2020). Spinach. In *Nutritional composition and antioxidant properties of fruits and vegetables* (pp. 181–195). Academic Press.

Murray, M., Dordevic, A. L., Cox, K. H., Scholey, A., Ryan, L., & Bonham, M. P. (2018). Study protocol for a double-blind randomised controlled trial investigating the impact of 12 weeks supplementation with a *Fucus vesiculosus* extract on cholesterol levels in adults with elevated fasting LDL cholesterol who are overweight or have obesity. *BMJ Open, 8*(12), Article e022195.

Muttagi, G. C., & Ravindra, U. (2020). Chemical and nutritional composition of traditional rice varieties of Karnataka. *Journal of Pharmacognosy and Phytochemistry, 9*(5), 2300–2309.

Mwalugha, H. M., Wakibia, J. G., Kenji, G. M., & Mwasaru, M. A. (2015). Chemical composition of common seaweeds from the Kenya coast. *Journal of Food Research, 4*(6), 28–38.

Mwirigi, F. M., & Theuri, F. S. (2012). The challenge of value addition in the seafood value chain along the Kenyan north coast. *International Journal of Business and Public Management, 2*(2), 51–55.

Naidoo, K., Maneveldt, G., Ruck, K., & Bolton, J. J. (2006). A comparison of various seaweed-based diets and formulated feed on growth rate of abalone in a land-based aquaculture system. *Journal of Applied Phycology, 18*, 437–443.

Nazurally, N., Facknath, S., Neetoo, S. H., Lalljee, B., Rao, A. R., & Ravishankar, G. A. (2022). Seaweeds in Mauritius: Bioresources, cultivation, trade, and multifarious applications. In *Sustainable global resources of seaweeds volume 1: Bioresources, cultivation, trade and multifarious applications* (pp. 129–142). Cham: Springer International Publishing.

Nishinari, K., & Fang, Y. (2017). Relation between structure and rheological/thermal properties of agar. A mini-review on the effect of alkali treatment and the role of agaropectin. *Food Structure, 13*, 24–34.

Nøkling-Eide, K., Tan, F., Wang, S., Zhou, Q., Gravdahl, M., Langeng, A. M., … Arlov, Ø. (2023). Acid preservation of cultivated brown algae *Saccharina latissima* and *Alaria esculenta* and characterization of extracted alginate and cellulose. *Algal Research, 71*, Article 103057.

Nordgård, C. T., & Draget, K. I. (2021). Alginates. In *Handbook of hydrocolloids* (pp. 805–829). Woodhead Publishing.

Norziah, M. H., & Ching, C. Y. (2000). Nutritional composition of edible seaweed *Gracilaria changgi*. *Food Chemistry, 68*(1), 69–76.

O'Doherty, J. V., Dillon, S., Figat, S., Callan, J. J., & Sweeney, T. (2010). The effects of lactose inclusion and seaweed extract derived from *Laminaria* spp. on performance, digestibility of diet components and microbial populations in newly weaned pigs. *Animal Feed Science and Technology, 157*, 173–180.

Ofori, R. O., & Rouleau, M. D. (2020). Willingness to pay for invasive seaweed management: Understanding how high and low income households differ in Ghana. *Ocean and Coastal Management, 192*, Article 105224.

Opiyo, M. A., Marijani, E., Muendo, P., Odede, R., Leschen, W., & Charo-Karisa, H. (2018). A review of aquaculture production and health management practices of farmed fish in Kenya. *International Journal of Veterinary Science and Medicine, 6*(2), 141–148.

Oucif, H., Benaissa, M., Ali Mehidi, S., Prego, R., Aubourg, S. P., & Abi-Ayad, S. M. E. A. (2020). Chemical composition and nutritional value of different seaweeds from the west Algerian coast. *Journal of Aquatic Food Product Technology, 29*(1), 90–104.

Oyesiku, O. O., & Egunyomi, A. (2014). Identification and chemical studies of pelagic masses of *Sargassum natans* (Linnaeus) Gaillon and *S. Fluitans* (Borgessen) Borgesen (brown algae), found offshore in Ondo state, Nigeria. *African Journal of Biotechnology, 13*(10).

Padam, B. S., & Chye, F. Y. (2020). Seaweed components, properties, and applications. In *Sustainable seaweed technologies* (pp. 33–87). Elsevier.

Pangestuti, R., & Kim, S. K. (2015). Seaweed proteins, peptides, and amino acids. In *Seaweed sustainability* (pp. 125–140). Academic Press.

Pangestuti, R., & Siahaan, E. A. (2018). Seaweed-derived carotenoids. In *Bioactive seaweeds for food applications* (pp. 95–107). Academic Press.

Peñalver, R., Lorenzo, J. M., Ros, G., Amarowicz, R., Pateiro, M., & Nieto, G. (2020). Seaweeds as a functional ingredient for a healthy diet. *Marine Drugs, 18*(6), 301.

Peng, Y., Wang, Y., Wang, Q., Luo, X., He, Y., & Song, Y. (2018). Hypolipidemic effects of sulfated fucoidan from *Kjellmaniella crassifolia* through modulating the cholesterol and aliphatic metabolic pathways. *Journal of Functional Foods, 51*, 8–15.

Pereira, L., Amado, A. M., Critchley, A. T., Van de Velde, F., & Ribeiro-Claro, P. J. (2009). Identification of selected seaweed polysaccharides (phycocolloids) by vibrational spectroscopy (FTIR-ATR and FT-Raman). *Food Hydrocolloids, 23*(7), 1903–1909.

Pérez-Lloréns, J. L., Critchley, A. T., Cornish, M. L., & Mouritsen, O. G. (2023). Saved by seaweeds (II): Traditional knowledge, home remedies, medicine, surgery, and pharmacopoeia. *Journal of Applied Phycology, 35*, 1–20.

Premarathna, A. D., Ahmed, T. A., Rjabovs, V., Hammami, R., Critchley, A. T., Tuvikene, R., & Hincke, M. T. (2024). Immunomodulation by xylan and carrageenan-type polysaccharides from red seaweeds: Anti-inflammatory, wound healing, cytoprotective, and anticoagulant activities. *International Journal of Biological Macromolecules, 260*, 129433.

Premarathna, A. D., Tuvikene, R., Fernando, P. H. P., Adhikari, R., Perera, M. C. N., Ranahewa, T. H., … Rajapakse, R. P. V. J. (2022). Comparative analysis of proximate compositions, mineral and functional chemical groups of 15 different seaweed species. *Scientific Reports, 12*(1), 19610.

Rahman, A., Nyambe, M. M., & Küpper, J. H. (2020). Namibian algae species: A review of their distribution, medicinal uses and chemical constituents. *Journal of Cellular Biotechnology, 6*(2), 139–159.

Rajauria, G., Foley, B., & Abu-Ghannam, N. (2017). Characterization of dietary fucoxanthin from *Himanthalia elongata* brown seaweed. *Food Research International, 99*, 995–1001.

Ratana-Arporn, P., & Chirapart, A. (2006). Nutritional evaluation of tropical green seaweeds *Caulerpa lentillifera* and *Ulva reticulata*. *Agriculture and Natural Resources, 40* (6 (Suppl.)), 75–83.

Rhein-Knudsen, N., Ale, M. T., Ajalloueian, F., & Meyer, A. S. (2017). Characterization of alginates from Ghanaian brown seaweeds: *Sargassum* spp. and *Padina* spp. *Food Hydrocolloids, 71*, 236–244.

Rhein-Knudsen, N., Ale, M. T., Ajalloueian, F., Yu, L., & Meyer, A. S. (2017). Rheological properties of agar and carrageenan from Ghanaian red seaweeds. *Food Hydrocolloids, 63*, 50–58.

Rizzo, G., Laganà, A. S., Rapisarda, A. M. C., La Ferrera, G. M. G., Buscema, M., Rossetti, P., … Vitale, S. G. (2016). Vitamin B12 among vegetarians: Status, assessment and supplementation. *Nutrients, 8*(12), 767.

Robal, M., Truus, K., Volobujeva, O., Mellikov, E., & Tuvikene, R. (2017). Thermal stability of red algal galactans: Effect of molecular structure and counterions. *International Journal of Biological Macromolecules, 104*, 213–223.

Rocha, C. P., Pacheco, D., Cotas, J., Marques, J. C., Pereira, L., & Gonçalves, A. M. (2021). Seaweeds as valuable sources of essential fatty acids for human nutrition. *International Journal of Environmental Research and Public Health, 18*(9), 4968.

Rogel-Castillo, C., Latorre-Castañeda, M., Muñoz-Muñoz, C., & Agurto-Muñoz, C. (2023). Seaweeds in food: Current trends. *Plants, 12*(12), 2287.

Roque, B. M., Venegas, M., Kinley, R. D., de Nys, R., Duarte, T. L., Yang, X., & Kebreab, E. (2021). Red seaweed (*Asparagopsis taxiformis*) supplementation reduces enteric methane by over 80 percent in beef steers. *PLoS One, 16*(3), Article e0247820.

Rothman, M. D., Anderson, R. J., Kandjengo, L., & Bolton, J. J. (2020). Trends in seaweed resource use and aquaculture in South Africa and Namibia over the last 30 years. *Botanica Marina, 63*(4), 315–325.

Rothman, M. D., Bolton, J. J., Stekoll, M. S., Boothroyd, C. J., Kemp, F. A., & Anderson, R. J. (2017). Geographical variation in morphology of the two dominant kelp species, *Ecklonia maxima* and *Laminaria pallida* (Phaeophyceae, Laminariales), on the west coast of southern Africa. *Journal of Applied Phycology, 29*, 2627–2639.

Rupérez, P., & Saura-Calixto, F. (2001). Dietary fibre and physicochemical properties of edible Spanish seaweeds. *European Food Research and Technology, 212*, 349–354.

Saluri, M., Kaldmäe, M., Rospu, M., Sirkel, H., Paalme, T., Landreh, M., & Tuvikene, R. (2020). Spatial variation and structural characteristics of phycobiliproteins from the red algae *Furcellaria lumbricalis* and *Coccotylus truncatus*. *Algal Research, 52*, Article 102058.

Sánchez-Machado, D. I., López-Cervantes, J., Lopez-Hernandez, J., & Paseiro-Losada, P. (2004). Fatty acids, total lipid, protein and ash contents of processed edible seaweeds. *Food Chemistry, 85*(3), 439–444.

Segbefia, A. Y., Barnes, V. R., Akpalu, L. A., & Mensah, M. (2018). Environmental location assessment for seaweed cultivation in Ghana: A spatial multi-criteria approach. *International Journal of Applied Geospatial Research (IJAGR), 9*(1), 51–64.

Shannon, E., & Abu-Ghannam, N. (2016). Antibacterial derivatives of marine algae: An overview of pharmacological mechanisms and applications. *Marine Drugs, 14*(4), 81.

Shannon, E., & Abu-Ghannam, N. (2019). Seaweeds as nutraceuticals for health and nutrition. *Phycologia, 58*(5), 563–577.

Škrovánková, S. (2011). Seaweed vitamins as nutraceuticals. *Advances in Food and Nutrition Research, 64*, 357–369.

Solarin, B. B., Bolaji, D. A., Fakayode, O. S., & Akinnigbagbe, R. O. (2014). Impacts of an invasive seaweed *Sargassum hystrix* var. *fluitans* (Børgesen 1914) on the fisheries and other economic implications for the Nigerian coastal waters. *IOSR journal of agriculture and veterinary*. *Science, 7*(7), 1–6.

Sultana, F., Wahab, M. A., Nahiduzzaman, M., Mohiuddin, M., Iqbal, M. Z., Shakil, A., … Asaduzzaman, M. (2023). Seaweed farming for food and nutritional security, climate change mitigation and adaptation, and women empowerment: A review. *Aquaculture and Fisheries, 8*(5), 463–480.

Tabarsa, M., You, S., Dabaghian, E. H., & Surayot, U. (2018). Water-soluble polysaccharides from *Ulva intestinalis*: Molecular properties, structural elucidation and immunomodulatory activities. *Journal of Food and Drug Analysis, 26*(2), 599–608.

Taylor, V. F., & Jackson, B. P. (2016). Concentrations and speciation of arsenic in New England seaweed species harvested for food and agriculture. *Chemosphere, 163*, 6–13.

Theron, M. M., & Lues, J. F. (2007). Organic acids and meat preservation: A review. *Food Reviews International, 23*(2), 141–158.

Tuvikene, R. (2021). Carrageenans. In *Handbook of hydrocolloids* (pp. 767–804). Woodhead Publishing.

Tuvikene, R., Truus, K., Kollist, A., Volobujeva, O., Mellikov, E., & Pehk, T. (2009). Gel-forming structures and stages of red algal galactans of different sulfation levels. In *Nineteenth international seaweed symposium: Proceedings of the 19th international seaweed symposium, held in Kobe, Japan, 26-31 March, 2007* (pp. 77–85). Netherlands: Springer.

Véliz, K., Toledo, P., Araya, M., Gómez, M. F., Villalobos, V., & Tala, F. (2023). Chemical composition and heavy metal content of Chilean seaweeds: Potential applications of seaweed meal as food and feed ingredients. *Food Chemistry, 398*, Article 133866.

Venugopal, V. (2011). *Marine polysaccharides: Food applications* (1st ed.). CRC Press.

Vieira, C., De Ramon N'Yeurt, A., Rasoamanendrika, F. A., D'Hondt, S., Tran, L. A. T., Van den Spiegel, D., … De Clerck, O. (2021). Marine macroalgal biodiversity of northern Madagascar: morpho-genetic systematics and implications of anthropic impacts for conservation. *Biodiversity and Conservation, 30*, 1501–1546.

Wakibia, J. G., Ochiewo, J., & Bolton, J. J. (2011). Economic analysis of eucheumoid algae farming in Kenya. *Western Indian Ocean Journal of Marine Science, 10*(1), 13–24.

Wang, Z., Wang, L., Yu, X., Wang, X., Zheng, Y., Hu, X., … Li, N. (2023). Effect of polysaccharide addition on food physical properties: A review. *Food Chemistry, 431*, 137099.

Williams, P. A., & Phillips, G. O. (2021). Introduction to food hydrocolloids. In *Handbook of hydrocolloids* (pp. 3–26). Woodhead publishing.

Xie, C., Lee, Z. J., Ye, S., Barrow, C. J., Dunshea, F. R., & Suleria, H. A. (2023). A review on seaweeds and seaweed-derived polysaccharides: Nutrition, chemistry, bioactivities, and applications. *Food Reviews International*, 1–36.

Yaich, H., Garna, H., Besbes, S., Paquot, M., Blecker, C., & Attia, H. (2011). Chemical composition and functional properties of *Ulva lactuca* seaweed collected in Tunisia. *Food Chemistry, 128*(4), 895–901.

Yaich, H., Garna, H., Besbes, S., Paquot, M., Blecker, C., & Attia, H. (2013). Effect of extraction conditions on the yield and purity of ulvan extracted from *Ulva lactuca*. *Food Hydrocolloids, 31*(2), 375–382.

Yokoyama, Y., Sasaki, M., & Sato, K. (2019). Nutrition intake among the Japanese elderly: An intergenerational comparison based on national health and nutrition survey scores. *Annals of Human Biology, 46*(4), 311–322.

Yoshinaga, K., & Mitamura, R. (2019). Effects of *Undaria pinnatifida* (Wakame) on postprandial glycemia and insulin levels in humans: A randomized crossover trial. *Plant Foods for Human Nutrition, 74*(4), 461–467.

You, K. M., & Sarkar, A. (2021). Oral tribology of polysaccharides. In *Handbook of hydrocolloids* (pp. 93–124). Woodhead Publishing.

Zhang, L., Liao, W., Huang, Y., Wen, Y., Chu, Y., & Zhao, C. (2022). Global seaweed farming and processing in the past 20 years. *Food Production, Processing and Nutrition, 4*(1), 23.

Zhao, Y., Shang, D., Ning, J., & Zhai, Y. (2012). Arsenic and cadmium in the marine macroalgae (*Porphyra yezoensis* and *Laminaria japonica*)- forms and concentrations. *Chemical Speciation & Bioavailability, 24*(3), 197–203.