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NUTRITIONAL AND SUSTAINABILITY ASPECTS OF ALGAE AND FUNGI SOURCES IN SEAFOOD ANALOGS – A REVIEW

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Abstract

Due to the growing acceptance of plant-based foods among consumers, the seafood analogs sector is rapidly expanding in variety, offering a wide range of available products. As plant-based analogs seem available for nearly all animal-based foods, this could guarantee a transition to more sustainable diets. In the formulated seafood analogs, all concerns are about consumers satisfaction of raw food materials, especially from the nutritive, structural, and sensory standpoints and beside this, economical price of final product. Notwithstanding that market for seafood analogs emerges from various products being developed by companies, algae and fungi not only as protein sources but also as sensory attributes appear increasingly useful raw materials. As such, additional exploration of algae and fungi sources are warranted which are high in proteins and available in large quantities. Therefore, a terse perspective of nutritional and sustainability aspects of algae and fungi sources is presented, drawing from a) nutritional status and health benefits of these sources; b) sustaining the potentials of algae and fungi sources; and c) introducing seafood analog market trends. Essentially, sensory attributes and the health benefits of algae and fungi make them a functional ingredient to apply in seafood analogs.

Key words: plant-based seafood, microalgae, seafood analogs, seaweed, sustainability

Seafood has been an integral component of the human diet since ancient times, offering a valuable supply of vital nutrients like ω-fatty acids, vitamins, and minerals. The depletion of natural animal-based seafood populations has prompted the emergence of seafood analogs (Azoff, 2021; FAO, 2022). Despite the growing acceptance of plant-based foods among consumers, the seafood analogs sector still faces a scarcity of high-quality products. Additionally, the fishing industry and coastal communities confront substantial challenges as fish migration patterns shift due to climate change (FAO, 2022). The aquaculture sector also experiences significant losses attributed to diseases like sea lice in farmed salmon, resulting in food waste and estimated annual economic losses of $6 billion (Akazawa et al., 2014). Furthermore, the sourcing and processing of seafood contribute significantly to greenhouse gas emissions (DeWeerdt, 2020). With the continuous growth of the global population and the escalating food demand, conventional practices in aquaculture may no longer suffice to meet these demands. Therefore, plant-based diets are attracting attention due to their health, environmental, and ethical advantages. The COVID-19 pandemic has further accelerated the adoption of plant-based diets among consumers (Koch et al., 2020). Considering these factors, seafood analogs have emerged as an alternative source to conventional seafood products, offering both economic and environmental benefits.

Seafood analogs market is governed by Europe due to the continuously approached research projects on food

novelty, consumer behavior, and sensory analysis start-ups (Cai et al., 2021; Bomkamp et al., 2022; Boukid et al., 2022, 2023; Mizuta, 2024). The global plant-based aquatic meat substitutes market size was valued at $42.1 million in 2021 and is predicted to reach $1.3 billion by 2031. To produce substitutes for seafood a variety of aquatic/marine sources, including fungi-based and algae (micro- and macroalgae like seaweed) ingredients are used. Besides, algae can be cultivated and harvested, whereas sea fungi (mainly found in the deep-sea) and other fungus proteins are cultivated. For aquatic animals (fish/shrimp/oysters/prawn) analog, plant-based proteins can be classified into two groups: 1. obtained from fresh or saltwater: algae and fungi, 2. obtained from cereal, legumes etc., vegetables, oils, pigments have been used in their mixed formula (Marwaha et al., 2020; Zhang et al., 2022). The economic advantages of the seafood analogs industry can be maintained by creating new jobs and significantly reducing greenhouse gas emissions, thus reducing the impact of energy on global climate change like other plant-based agricultural food industries (Nowacka et al., 2023).

Seafood analogs demonstrate similar nutritional benefits when compared to traditional seafood, particularly the wide range of nutrients, from protein, vitamins, to minerals. Moreover, some seafood analogs are source of α-linolenic acid (ALA), a type of ω-3 fatty acid which basically come from algae and fungi ingredients (Charoensiddhi et al., 2017). Some types of seafood analogs are also fortified with other nutrients such as vitamin B_{12}, typically found in animal-based foods. Therefore, daily nutrient requirements could be fulfilled without relying entirely on animal-based sources, which is especially important for vegetarians and vegans at risk of nutrient deficiencies. Alternative seafood comprises all plant-based, fermentation-derived, and cell-based (from cultivated cells) aspects. They have been formulated to imitate the taste, texture, appearance, and nutritional values of conventional animal seafood (Marwaha et al., 2020). One of the most significant challenges that seafood analogs industry faces is the development of high-quality, tasty products that mimic traditional animal seafood. Recent advancements have lead to create seafood analog products that taste not only like traditional seafood but also reveal similar mouthfeel/texture. The scalability of seafood analog production remains challenging. There is a need to explore marine/aquatic taste and nutritive alternatives such as algae and marine/aquatic fungi, which can be grown in large quantities and are high in protein and other nutrients. Further, it is important to know how the health aspect of nutritional compositions in these products relates to potential uses in food. To supplement existing information, therefore, a terse perspective of nutritional and health benefit aspects of algae and fungi sources in the seafood analogs is presented drawing from a) sources from aquatic/marine environment and their nutritional status; b) health benefits of different microalgae and their applications; c) sustaining the potentials of culturing micro- and macroalgae and seafood analogs; d) some examples of companies in the seafood analog industry.



Figure 1. Images of brown, green, and red seaweed species

Table 1. Chemical composition of different seaweeds (all results represented in g/100 g dry weight)

Brown seaweeds	Protein	Lipid	Ash	CHO	Dietary fiber	References
1	2	3	4	5	6	7
Alaria esculenta	9.11	1.30–1.50	24.56	–	–	Mæhre et al. (2014)
Ascophyllum nodosum	5.2–8.70	3.62–4.7	23.5–30.89	–	5.5–6.7	Lorenzo et al. (2017); Meng et al. (2022)
Bifurcaria bifurcata	8.92	6.54	31.68	–	–	Lorenzo et al. (2017)
Colpomenia sinuosa	9.2	1.5	28.1	32.1	–	Rohani-Ghadikolaei et al. (2012)
Cystoseira compressa	8.91	1.83	32.04	39.62	–	Oucif et al. (2020)
Cystoseira stricta	14.14	2.71	24.61	35.45	–	Oucif et al. (2020)
Durvillaea antarctica	10.80	0.40	26.00	54.60	–	Caballero et al. (2022)
Durvillaea incurvata	6.5	1.9	32.2	–	4.3	Véliz et al. (2023)
Fucus vesiculosus	6.11–12.99	2.65–3.75	20.71–20.92	–	–	Mæhre et al. (2014); Lorenzo et al. (2017)
Laminaria digitata	5.31–9.12	0.68–1.13	24.43–25.40	55.80	–	Mæhre et al. (2014); Malafronte et al. (2021)
Laminaria hyperborea	5.02	1.14–1.42	28.75	–	–	Mæhre et al. (2014)
Laminaria japonica	7.2–13.1	0.4–1.8	20.8–64.3	–	6.3–12.4	Meng et al. (2022)
Lessonia berteroana	8.60	1.60	38.80	–	8.10	Véliz et al. (2023)
Lessonia flavicans	11.09	0.48	26.95	–	8.53	Meng et al. (2022)
Lessonia nigrescens	10.42	0.87	31.04	–	10.54	Meng et al. (2022)
Lessonia spicata	8.40	2.00	35.70	–	9.50	Véliz et al. (2023)
Lessonia trabeculata	7.90	1.30	37.50	–	8.80	Véliz et al. (2023)
Macrocystis pyrifera	6.80–10.40	1.10–1.60	34.80–50.80	–	7.20–13.80	Meng et al. (2022); Véliz et al. (2023)
Pelvetia canaliculata	5.7	3.7–5.8	21.2	–	–	Mæhre et al. (2014)
Saccorhiza polyschides	14.44	1.1	28.15	45.6	–	Rodrigues et al. (2015)
Sargassum ilicifolium	8.9	2.0	29.9	32.9	–	Rohani-Ghadikolaei et al. (2012)
Sargassum muticum	11.0–16.9	1.3–1.6	14.6–24.9	49.3	8.4–12.4	Rodrigues et al. (2015); Meng et al. (2022)
Undaria pinnatifida	16.8–28.2	2.3–2.8	17.2–43.9	–	4.7–6.1	Meng et al. (2022)
			Red seaweeds			
Acrosorium sp.	16.70	1.70	29.10	–	5.50	Véliz et al. (2023)
Chondracanthus chamissoi	10.90	0.90	21.80	–	2.50	Véliz et al. (2023)
Corallina elongata	5.85	0.64	76.42	13.40	–	Oucif et al. (2020)
Cryptonemia obovata	18.00	1.30	22.90	–	3.40	Véliz et al. (2023)
Gracilaria changii	12.57	0.30	40.30	41.25	64.74	Chan and Matanjun (2017)
Gracilaria chilensis	15.00	2.10	22.60	–	5.50	Véliz et al. (2023)
Gracilaria corticata	19.3	1.8	23.1	43.0	–	Rohani-Ghadikolaei et al. (2012)
Gracilaria gracilis	20.2	0.6	24.8	46.6	–	Rodrigues et al. (2015)
Grateloupia turuturu	22.50–22.90	2.20–2.60	18.50–20.52	43.20	60.40	Denis et al. (2010); Rodrigues et al. (2015)
Hypnea valentiae	16.5	2.8	21.8	31.8	–	Rohani-Ghadikolaei et al. (2012)
Osmundea pinnatifida	23.8	0.9	30.62	32.4	–	Rodrigues et al. (2015)
Palmaria palmata	12.26	1.33–1.39	42.20	–	–	Mæhre et al. (2014)
Sarcodiotheca gaudichaudii	18.90	2.40	29.90	–	6.00	Véliz et al. (2023)
Vertebrata lanosa	11.56	1.30–1.80	28.78	–	–	Mæhre et al. (2014)
			Green seaweeds			
Caulerpa lentillifera	9.26	1.57	22.20	64.00	2.97	Nguyen et al. (2011)
Caulerpa racemosa	11.39	1.03	7.97	71.67	–	Hao et al. (2019)
Cladophora rupestris	3.42	0.63–0.88	77.80	–	–	Mæhre et al. (2014)

Table 1 – contd.

1	2	3	4	5	6	7
Codium tomentosum	18.8	3.6	35.99	32.8	–	Rodrigues et al. (2015)
Enteromorpha compressa	13.61	1.00	26.36	46.11	–	Oucif et al. (2020)
Enteromorpha intestinalis	10.5–11.33	1.03–2.90	22.4–55.29	35.5	–	Mæhre et al. (2014); Rohani-Ghadikolaei et al. (2012)
Ulva sp.	15.90–20.23	3.11–3.90	17.28–19.81	–	43.14–47.16	Uribe et al. (2019); Véliz et al. (2023)
Ulva lactuca	8.65–12.54	0.98–2.62	27.13–29.31	42.81	–	Mæhre et al. (2014); Oucif et al. (2020)
			Microalgae			
Acutodesmus dimorphus	28.1	18.8	14.5	38.6	–	Tibbetts et al. (2015)
Botrycoccus braunii	39.1–39.9	24.9–34.4	5.4–7.2	18.5–30.6	–	Tibbetts et al. (2015)
Chlamydomonas reinhardtii	64.76	12.60	–	22.64	–	Mahdy et al. (2014)
Chlorella vulgaris	63.38–63.40	4.80–18.01	6.20	18.61–25.70	–	Mahdy et al. (2014)
Dunaliella salina	8.46	11.47	0.03	85.58	–	Pirwitz et al. (2016)
Nannochloropsis sp.	36.40	19.05	8.91	12.40	–	Zhang et al. (2016)
Nannochloropsis granulata	17.9–33.5	23.6–47.8	6.7–6.9	27.4–36.2	–	Tibbetts et al. (2015)
Neochloris oleoabundans	30.1	15.4	16.7	37.8	–	Tibbetts et al. (2015)
Porphyridium aerugineum	31.6	13.7	8.9	45.8	–	Tibbetts et al. (2015)
Scenedesmus sp.	33.13	21.80	10.50	34.60	–	Mahdy et al. (2016)
Spirulina sp.	48.50	5.89	8.20	10.80	–	Zhang et al. (2016)
Spirulina platensis	76.65	2.45	14.56	6.46	4.07	Seghiri et al. (2019)
Tetraselmis chuii	46.5	12.3	16.2	25.0	–	Tibbetts et al. 2015)

Nutritional aspects of algae and fungi sources in seafood analogs

Algae sources

Algae sources can be classified into macroalgae and microalgae. Macroalgae are primarily cultivated seaweed species such as *Saccharina japonica*, *Undaria pinnatifida*, and *Sargassum fusiforma* which belong to brown seaweeds. Red seaweeds such as *Neopyropia/Pyropia/Porphyra* sp., *Eucheuma* sp., *Kappaphycusalvarezii*, and *Gracilaria* sp. are also cultivated, along with green seaweeds like *Ulva clathrata, Monostromanitidum, Caulerpa* sp., *Ulva* sp., and *Oedogonium termedium* (Purcell-Meyerink et al., 2021), and would create analogs for fish, shrimp, oysters, and prawns. Images of brown, green, and red seaweed species are given in Figure 1. Microalgae and cyanobacteria offer an abundance of valuable compounds such as proteins, lipids, carbohydrates, carotenoids, and vitamins (Priyadarshani and Rath, 2012). Seafood analogs are comprised of aquatic plants, algae, and fungi and these are mainly used as nutrient fortification, flavoring agent, and texturizer in food industry. The chemical composition of seafood analogs mainly depends on the species, place of cultivation, atmospheric conditions, and harvesting period. The proximate composition of several seaweeds is listed in Table 1.

Seaweed and their ingriedients

Seaweeds possess a wealth of macro- and micronutrients making them highly promising and sustainable resources for the production and consumption of desirable food. Certain types of brown seaweeds (*Laminaria* sp. and *Nereocystis* sp.), red seaweeds (*Porphyra* sp. and *Rhodymenia palmata*), as well as the derived foods from these species, have been classified as "Generally Recognized as Safe (GRAS)" by the U.S. Food and Drug Administration (Charoensiddhi et al., 2017). From a nutritional standpoint, seaweeds remain cultivated for their functional polysaccharides and/or mineral content, further enhancing their appeal (Bizzaro et al., 2022). Carbohydrates, as abundant biochemical constituents in seaweeds, represent the main energy source developed from diverse metabolic routes (Oucif et al., 2020). Also, the ash contents provide a rough estimate of total mineral contents of the seaweed. Further, seaweeds serve as an excellent natural source of iodine, with levels ranging from 21–3500 mg/kg, surpassing by 10–1400 times those found in marine fish (Mæhre et al., 2014). Seaweed is an aquatic product that has been consumed in South Asian traditional foods. Recently, seaweed powder, as an ingredient, has shown an uprising popularity/trend in the world of plant-based diets. Seaweed protein is packed with essential vitamins and minerals, making it an ideal ingredient for health /wellness products. Seaweed protein is known as a complete protein, meaning it contains all nine essential amino acids that the body needs. Additionally, seaweed protein has a low content of fat and carbohydrates. Aside from its nutritional benefits, seaweed can balance

the positive and negative factors of the cultivation system and is known as environmentally friendly (García-Poza et al., 2020). Seaweeds contain a wide range of macro minerals, including sodium, calcium, magnesium, potassium, chloride, sulfate, and phosphorus, as well as microminerals (such as iodine, iron, zinc, copper, selenium, manganese, boron, nickel, cobalt, etc) (Peñalver et al., 2020). However, seaweeds can take up, store, and accumulate heavy metals, which may be detrimental to human health. The arsenic content (4.9–64 mg/kg dm) of algae was found quite high; however, the content of cadmium (0.092–3.8 mg/kg) and mercury (0.005–0.047 mg/kg dm) was determined low for common Norwegian seaweeds (Mæhre et al., 2014). As shown in Table 1, seaweeds exhibit varying lipid contents, which differ across different species. Red seaweeds, for instance, are rich in palmitic, oleic, arachidonic and eicosapentaenoic acid (EPA), while brown seaweeds display elevated levels of myristic, palmitic, oleic, linoleic, ALA and arachidonic acids. On the other hand, green seaweeds contain palmitic, oleic, vaccenic, linoleic and ALA (Kumari et al., 2010; Xu et al., 2023; Pereira et al., 2024).

Microalgae have been consumed as food, supplements, and additives in all over the world for 4000 years due to their positive effects on human health. Aquatic plant-based seafoods are sustainable sources of protein, minerals, and fiber, and they also contain essential amino acids, pigments, and PUFAs. Volatiles such as dimethylsulfide, fatty acids-derived compounds, TMA, glutamic acid, alanine and arginine and 5′-ribonucleotides were identified as important seafood aroma compounds in microalgae (Coleman et al., 2022). Furthermore, it has been stated that some microalgae such as *Rhodomonas salina, Tetraselmis chui* and *Phaeodactylum tricornutum* could have stronger seafood flavors (Coleman et al., 2022). Using microalgae (*Nannochloropsis oceanica*) up to 30% with pea proteins into fishcake analog had the potential to contribute to the development of modified textural and rheological properties and unique digestive characteristics (Zhao et al., 2024). It has been found that brown algae provide a three-dimensional cell growth and differentiation environment for steak-like cultivated meat. Therefore, brown algae-based products have the potential to emulate the textural characteristics of traditional fish meat (Lee et al., 2024). In addition to blue-green algae, seaweed is also a seafood analogs ingredient consumed by humans in various forms. Seaweed has been recognized as "the future plant-based food." As studies on plant-based sea ingredients such as algae and seaweed increase, awareness and interest in seafood analogs have rapidly increased in Western countries as well. Seaweeds also contribute to human health with their properties including antihyperlipidemic, anticancer, antidiabetic, antioxidant, anti-inflammatory and microbiota-enhancing (Montero et al., 2017). These ingredients in the seafood analogs contribute to the treatment of obesity, diabetes, hypertension, and cardiovascular diseases, as well as providing anti-inflammatory, antioxidant, and anticancer properties that benefit human health (Figure 2).

Fungi and their potentials

Despite the early studies mainly focused on seaweeds, marine-derived fungi represent a rich and promising source of biologically active compounds. Most of these microorganisms thrive in unique and extreme habitats, and endowing them with the capability to produce unusual secondary metabolites (James et al., 2012) which possess various health-promoting effects, including anticancer, antibacterial, antiplasmodial, anti-inflammatory and antiviral activities (Bhadury et al., 2006; Deshmukh et al., 2018; Mia et al., 2021). To date, more than 1000 new compounds have been isolated from the marine fungi (Gomes et al., 2015). The fatty acid profile of four marine fungal cultures (*Trichoderma pesudokoningii, Curvularia lunata, Penicillium chrysogenum*, and *Aspergillus niveus*) ranged from 12 to 24 carbons. In all cultures, the percentage of unsaturated fatty acids exceeds that of saturated fatty acids, and while they share similar fatty acid profiles, individual concentrations differ (Devi et al., 2006).

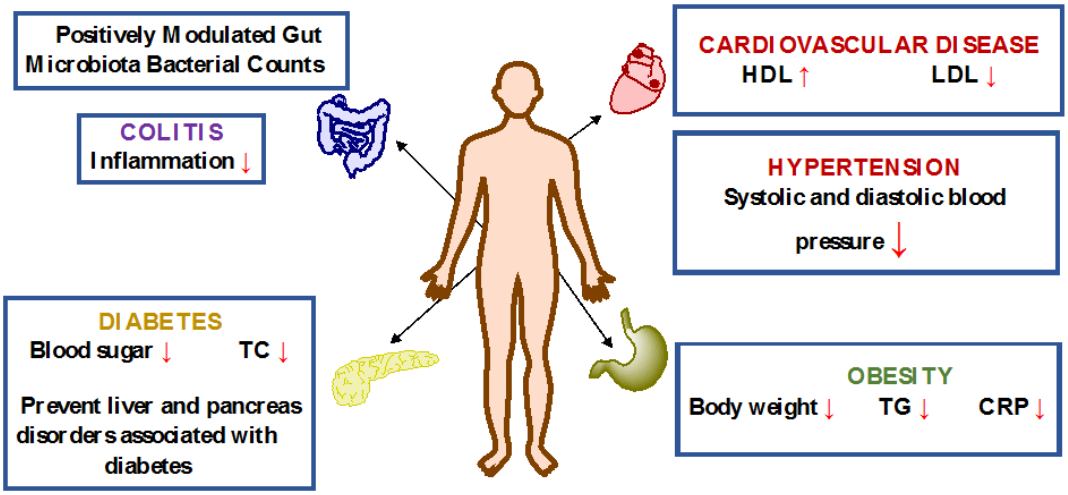


Figure 2. Therapeutic effects of plant-based seafoods

Marine fungi serve as an important source of secondary metabolites. The contribution of marine-based therapeutics can be gauged from the fact that during 1981–2002, more than half of the FDA-approved drugs originated from aquatic life. By establishing national and international aquaculture centers, many of these novel metabolites can be cultivated and produced (Deshmukh et al., 2018). Aquatic fungal communities have also been proposed in the literature (Calabon et al., 2023). Carotenoid pigments derived from *Phaffia rhozyma* or *Yarrowia lipolytica* yeast, are employed in seafood analogs to provide color (Mahmud et al., 2024). The Incorporation of DHA and EPA into seafood analogs ensures that they offer the same nutritional benefits as their seafood counterparts. Fish oils could be replaced by *Yarrowia lipolytic*a strains, as an alternative to produce EPA oil (Ghazani and Marangoni, 2022). New products with seafood-like textures using fungi to ferment seaweed have been also studied. Fungal fermentation of edible red algae *Neopyropia yezoensis*, has been proposed to release the contained EPA by breaking down the cell walls or production of structural analogs (Nagao et al., 2022, Inoue et al., 2024). All these studies demonstrate that fungi have the potential to imitate seafood by conducting various fermentation rates and growth conditions, making them viable substitutes that resemble both flavor and texture.

Other aquatic sources

Plant-based aquatic sources are vegetables such as water spinach, watercress, and lotus root, which thrive in aquatic conditions. Watercress (*Nasturtium officinale* R. Br.) is a perennial leafy green crop adapted to growth in aquatic environments, known for its peppery flavor (Hibbert et al., 2023). Aquatic legumes like water caltrop and water chestnut also grow in water and are consumed for their edible seeds or corms (Li et al., 2007; Aasim et al., 2018). Additionally, paddy rice – a staple food for many cultures – is cultivated in flooded fields. Therefore, paddy rice proteins are considered suitable for use in aquatic plant-based seafood analogs in the future (Kassam, 2021). Duckweed, with a protein content of up to 45 percent, has been consumed in Laos, Thailand, Vietnam, and parts of Africa for centuries. Wolffia, a genus of duckweed family, has been introduced as a new aquatic protein in Western diets (Tarver, 2016; Appenroth et al., 2018; On-Nom et al., 2023; Li et al., 2024).

The marine plant *Zostera marina*, commonly known as eelgrass or sea wrack, has historically been used by some indigenous people to make flour for bread-like product and beverages. This plant could be introduced as a new source to the seafood analog market (Pérez-Lloréns and Brun, 2023).

Sustainability roles of seafood analogs

Population growth and increasing awareness of safe and sustainable food sources are leading to fundamental changes in human diets. Following the COVID-19 pandemic, the adoption of vegetable-based and plant-based diets has gained importance (Marwaha et al., 2020; Kaur and Reddersen, 2022). Moreover, to provide enough food to the global population, although agriculture, livestock, and aquaculture products are overproduced, food shortages persist in specific regions and countries. This overproduction leads to unsustainable production systems that harm natural ecosystems and environment. Environmental elements like soil, water, and air are polluted by the intensive use of pesticides, toxic agricultural chemicals, and wastewater yearly. To handle these, more sustainable food production chains and diets are required. Moreover, international organizations and governments in cooperation with scientists and producers should collaborate to find solutions (Kaur and Reddersen, 2022). For instance, Spain has considered imposing taxes on animal-origin foods like meat and fish to protect the environment (Karwacka et al., 2020).

Fish – whether fresh, frozen, or processed – serve as the primary raw material in various traditional cooking recipes (Olsen et al., 2021). Since there has been an increase in seafood consumption over the last 50 years, exporting aquatic food products has become more popular. For instance, European countries consume almost 12.45 million tons of seafood each year – yet domestic production accounts for only approximately 5.40 million tons; therefore, as much as 55% of seafood consumption must be met through imports (Gómez and Maynou, 2021). Microalgae-based meat/fish substitutes should align with consumer expectations in terms of taste while emphasizing sustainability and innovation. According to a survey from Singapore, the perceived healthiness of microalgae appears to impact consumer acceptance (Wassmann et al., 2024).

Seafood analog's role in the sustainable food system

Beyond personal health care and animal rights awareness, there is growing concern about the environmental impacts of food production. To design more sustainable food systems, various sources and diets have been recommended (Farmery et al., 2017). Vegetable-rich diets, such as the Mediterranean diet or pescatarian diet, minimize environmental impacts. Each food product has a specific environmental footprint that can either positively or negatively affect the environment. Notably plant-based marine food products have fewer carbon footprints and generate less water waste, making them more environmentally friendly. To evaluate the environmental impacts of food products, life cycle assessment (LCA) has been widely used. From production to consumption all supply chains can be evaluated. LCA helps us to understand the impacts of whole diets and design more sustainable patterns of consumption. Based on the LCA approach, a sustainable diet tends to favor plant-based diet options over animal-based ones (Farmery et al., 2017). Utilizing LCA and methods of calculating the environmental footprint the European Commission has aimed to measure the environmental impact of products and enterprises across

various industries over the past decade. Consumers will be informed by environmental footprint information on product labels, allowing them to make informed choices (Karwacka et al., 2020).

Overfishing and the decline of fish populations

Fish serves as important nutrient resource in human diets, particularly for rural low-income communities (Clausen and York, 2008; Chen et al., 2021). Further, global population increases with food resource challenges. Fish Base data has shown human overfishing remains among the greater threats to aquatic environment health, which alters the global native fish species. As fisheries biologist Daniel Pauly calls it: "fishing down the food chain", further depicting the possibilities of overfishing influence on the ocean trophic structure. Since the late 1980s, global fish production appears to be on a gradual decline even as warnings are screamed by environmentalists alongside increased international regulatory efforts. Noteworthy to mention is a study of Millennium Ecosystem Assessment that further reiterated the effects of overfishing. Specifically, the industrial fishing activity in the world's oceans brought about 90% reduction of all large predatory fish (such as cod, tuna, swordfish, and salmon) (Clausen and York, 2008). Clearly, overfishing induces a decline in the fish population and biodiversity/health of the ecosystem. Therefore, it is imperative that overfishing from natural seas and oceans is handled with moderation. Notably also, the aquaculture industry production of farmed aquatic animals has consistently increased, reaching 178 million tons in 2020. Particularly in China, the farmed aquatic food production has been above the rest of the world combined since 1991 (Chen et al., 2021, Issifu et al., 2022). As of 2020, China was reported the major aquaculture producer with 35% percent of the global total, followed by India (8%), Indonesia (7%), Vietnam (5%), and Peru (3%) (FAO, 2022).

Seafood analogs sustainability

For emphasis, climate changes and pollution cause harm to marine ecosystems, which would contribute to the decline in biodiversity (Akita et al., 2022). Moreover, the increases in population alongside chronic diseases require that more emphasis be given to food products that provide functionally healthy diets and this calls for more food alternatives that embrace innovative sustainable technologies. Thus, a promising question could then be: which diet is more sustainable? A 2017 meta-analysis of 369 published LCA studies about plant and animal-source foods showed plant-based foods with the lowest, and ruminant meat with the highest impact. Despite this, seafood species revealed quite low (e.g., herring) to high (e.g., lobster) ranges (Koehn et al., 2022). Feasibly, seafood analogs would aim to provide much more sustainable food sources with enhanced nourishment/quality. This is where the concept of sustainability would play an excellent role in assuring resource abundance/availability and less seasonality notwithstanding the dependence on raw material supply (Lankatillake et al., 2023). Generally, the production of seafood analogs would provide a lower carbon footprint compared to meat-based foods (Koehn et al., 2022).

It is worthy to mention the importance of seaweed as a promising marine protein, which depicts a sustainable crop that requires neither fertilizers nor pesticides to grow, thus making it eco-friendly. With the increasing demand for plant-based protein sources, seaweed protein is poised to become a core ingredient in the health and plant-based seafood industry. From protein bars to vegan protein powders, seaweed protein is already being used in a variety of products and according to its unique aquatic taste and flavor in seafood analogs. Additionally, seaweed farming was reported to improve the health of oceans by absorbing excess nutrients and carbon dioxide from the water (Kinley et al., 2020).

Seafood analogs socio-economic sustainability

When sustainable social and economic aspects of the seafood analog products are considered, it means increased efficiency, the creation of cheap and high-quality products, and the creation of new jobs. The principles of sustainable development would involve both framework design and structural knowledge/understanding of products/processes. With the use of raw materials that have the lowest possible negative impact on the environment through CO_2 emission and greenhouse gases, no excessive water or energy resources would need to be applied. International organizations would have to force governments to venture into the implementation of sustainable development approaches across relevant sectors as well as industrial products. For example, in Poland Resolution No. 123 of 15 October 2019 on the adoption of the "Strategy for the sustainable development of rural areas, agriculture, and fisheries" (Karwacka et al., 2020). According to the rising number of polluted oceans, rivers, and seas, there is increasing attention to the food security and safety of aquatic plants/animals. Moreover, the consumption of wild aquatic products by humans continues to pose serious health concerns/risks (Chen et al., 2021). Social sustainability is manifested in food security. Seafood analogs promise better social sustainability in the future. Equitable work relations and fair workers' incomes (e.g., crew, seafood processors) are usually not incorporated as part of sustainable fishing plans nor embodied using certification schemes in seafood products consumers purchase (Gómez and Maynou, 2021). Socio-economic sustainability in aquatic product production requires the support of local fishers, which would help provide food, especially for small scale (local) consumption. That is why it is necessary to reduce pressure on global fishers to allow both commercial species and oceans ecosystem to recover. Also, the areas of the plant- and cell-based seafood value chains offer the greatest employment opportunities, especially among marginalized groups as well as women (Marwaha et al., 2020).

Seafood analog products industry

There is a recommended amount of seafood consumption for positive health outcomes by national dietary guidelines (Farmery et al., 2017). On the other hand, recently there are serious concerns about contaminated sea waters with heavy metals like mercury and macro/microplastic residues in seafood. So, when we think about the health aspects of seafood consumption, we should think twice about the safety of seafood resources and the polluted sea effects on seafood. Therefore, marine ecology systems require further exploration/measurements to ensure health risks are minimized, especially for the consumption of wild seafood (Farmery et al., 2017). Besides overfishing problem that confronts the marine environment, which restricts the availability of marine/aquatic species (Issifu et al., 2022), the global diets appear to focus on more substantial contributions to protect the environment, given the challenges of chronic diseases, hence the need for increased vegan/vegetarian food substitutes as a healthy lifestyle (Marwaha et al., 2020). Today, the hope continues to persist for the above-mentioned primary factors to drive the progress of the aquatic/marine plant food industry.

Some seafood analog companies and their products with the main ingredients are summarized in Table 2. Distribution channels of seafood analog markets are supermarkets and hypermarkets, convenience stores, online, and others (Khan, 2012; Mordor Intelligence, 2024). Among these distribution channels, the online platform serves as a popular medium for the purchase of packaged seafood analogs, potentially given by easy availability alongside benefits like availability of information, time-saving shopping, and home facility. Especially after COVID-19 pandemic online shopping has become one of the habits and is more popular among people all around the world (Koch et al., 2020).

One of the increasing numbers of seafood analogs is aquatic algae-seaweeds which are produced in both land-based and sea-based aquaculture (Figure 3) (Stedt et al., 2022). The seaweed genus *Asparagopsis* was reported to emerge as an effective agent in innovative cleaner production for the wider agriculture sector. Seaweed is believed to remove CH_4 emissions of approximately 230 $MtCO_2e/y$ if it is replaced in diets at 20% instead of dairy and beef (Kinley et al., 2020). Different technologies could be applied to produce seafood analog products. Extrusion and shear cells are leading technologies; however, both require specialized equipment and high-energy inputs. The main concept of these machines is mixing different ingredients to reach the desired texture and homogeneous structure. Under pressure and at different temperatures these technologies make this possible. However, for smaller companies, a simpler, cheaper, and more energy-efficient device to prepare plant-based seafood products is recommended. A start-up company (Rival Foods) is one of the small companies that adopted a cylinder-in-cylinder device to produce plant-based meat alternatives. The fundamental process is based on mixing and heating of ingredients, and it seems the same as extrusion (Zhang et al., 2022). Besides, the market trends of seafood analogs can include a) formulated plant-based seafood sensory analyses are the main challenging point to preparing them to be accepted and shifting consumer tastes; and b) growing trend cases huge corporations and markets that appear to be gaining ground in different parts of the globe.

Table 2. Some examples of seafood analog products in market

Company	Product	Main ingredients	Website
Bettafish	TU-NAH Can	Pea and broad bean proteins, seaweed	www.bettafish.co
	TU-NAH Jar (Natur Olive, Tomato, Chili)	Seaweed, textured broad bean protein	
	TU-NAH Pizza	European seaweed, fava beans	
Hooked Foods	Tuna substitute (Toonish)	Pea protein, algae protein,	www.hookedfoods.com
	Smoked salmon substitute (Salmoonish)	Soy, pea, wheat proteins, algae oil	
	Spread mix (Toonish mayo and Toonish curry)	Wheat, soy, algae	
Jens Møller Products	Skagen	Wheat and soy proteins, algae, seaweed caviar extract	www.caviart.com
	Masago/tobiko substitute (Tosago®) Fish roe substitute (Cavi·Art®) Fish dish (Food·art®)	Seaweed	
Mimic Seafood	Tunato®	Tomato, olive oil, algae	www.mimicseafood.com
	Roemato®	Tomato water, macroalgae (kombu), agar agar	
Odontella	Salmon slices	Macroalgae, pea protein	www.odontella.com
Red Tiger	Seaweed (Kelp) Caviar	Brown Seaweed (*Laminaria hyperborea*)	https://alimar-tr.com
The Better Meat Co.	Fish Filet, Crab	Rhiza Mycoprotein	https://www.bettermeat.co

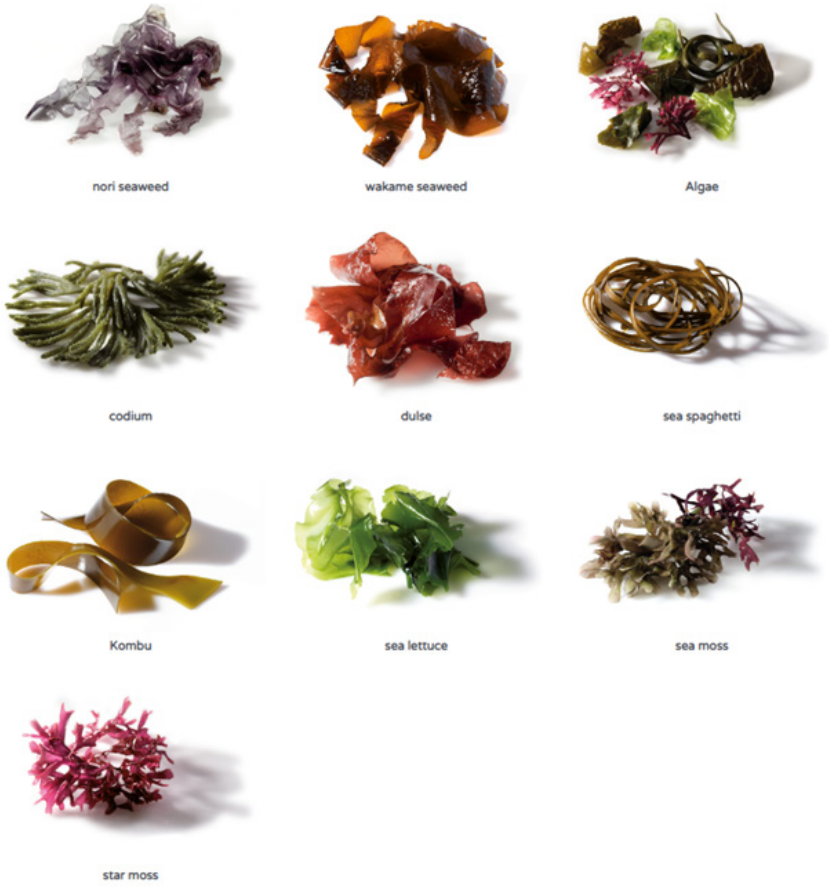


Figure 3. Various natural algae seaweeds from Galicia cultivated and manually harvested PORTO-MUIÑOS S.L. brand, Spain (pictures source: https://www.portomuinos.com/Algas/?lang=en)

Categorizing and enhancing seafood analogs

The availability of seafood analogs could reduce the environmental problem associated with the depletion of seafood population, provide veggie/vegetarian consumers to enjoy marine foods by creating alternatives to real seafood, as well as ensuring more sustainably in seafood supplement chain (Zhang et al., 2022). At the same time, the authorities/scholars appear to be focusing on ensuring the quality of seafood analogs for the consumer, which should be seen to help companies and businesses to bloom and make progress (Freitas et al., 2020). Besides, national/international food standards are imposing new rules and regulations to ensure safe and secure animal-friendly production and lower pollution levels in food products. In this context, the main aims of plant-based seafood industry can be categorized as: a) producing safe seafood analogs and enhancing taste, texture, and overall sensory properties of new formulated final products; b) to producing products of competitive prices compared to the animal-based products they are imitating; c) fortification and enrichment of seafood analogs with functional components; d) increasing the nutritional quality, and e) expanding supply chain, distribution and markets (Marwaha et al., 2020, Freitas et al., 2020).

In Figure 4 value chain of plant-based seafood has been summarized. More so, implementing new technologies such as cold plasma, capsulation, nanotechnology, etc., has been seen as the means to improve plant-based seafoods. However, to provide acceptable plant-based seafood alternatives the nutritional value, mainly protein compositions, should be considered (Kazir and Livney, 2021). The most challenging step of imitating original seafood is related to its flavor, appearance, and texture. Since 2020, there has been a flash growth of various start-ups and companies which provide different tastes and plant-based seafood, and research/development departments of companies appear looking for new and functional ingredients. Another instance is the muscle texture of real meat being imitated by novel micro-extrusion techniques (Marwaha et al., 2020). Nonetheless, there appears to be a challenge in assuring the quality of plant-based seafood, as in the case of complex supply chains to provide raw ingredients from sea. The slogan "from farm to fork" in the seafood case could be "from sea to fork" and this means the necessity of a more transparent food supply chain e.g.: who is responsible for what and over which time frame. Monitoring measurement and traceability of the supply chain is the main key (Freitas et al., 2020).

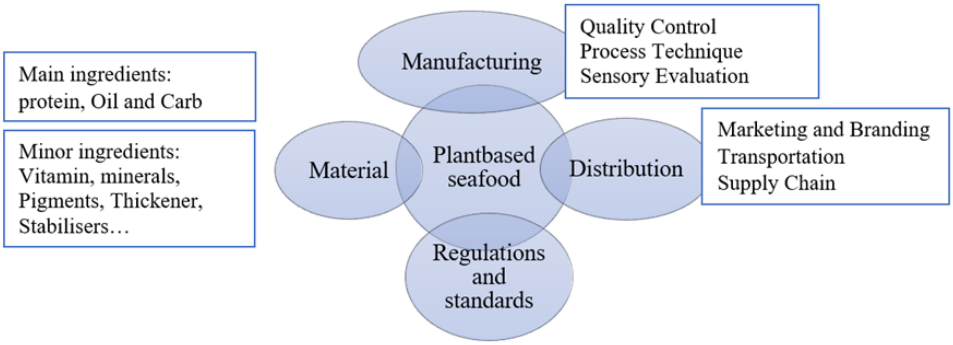


Figure 4. Value chain mapping of plant-based seafood (modified from Choudhury et al., 2020)

Concluding remarks and future hopes

The nutritional composition, health benefits and potential applications of algae and fungi sources have been discussed. In recent years, world aquaculture production of farmed aquatic plants has regularly increased. An example is China, which is considered as the country where the most farmed aquatic food is being cultivated/obtained. Aquatic plant production developments depend on the regional growth potential and financial and government regulations. For example, in the US, considering environmental issues federal and local government can delay or stop permitting approval of aquaculture. The application of smart aquatic food farms in the food sector is being developed to achieve seafood system sustainability. Monitoring water quality, feeding level of fish, identifying abnormal phenomena, automatic live fish identification, and live fish species classification can be approved by smart farm equipment or systems. There is a need for increased cooperation between plant aquaculture growers and plant-based seafood producers, as this can help them to achieve a sustainable aquaculture industry, and this can be considered as an advisable future strategy for best results. Notably, plant-based seafood industry has appeared in recent years to increasingly emerge as a promising solution, which would help to address the challenges posed by traditional animal-based seafood production, including overfishing, climate change, and animal welfare concerns. More so, the cultivation of seaweed, microalgae, and fungi has opened new possibilities to produce high-quality, nutritious, and sustainable plant-based seafood products. While there are still challenges to overcome, the plant-based seafood product industry's potential for economic and environmental benefits remains significant. With further advancements in the field of food science and technology, the plant-based seafood industry is poised to become a vital component of a sustainable and ethical food system. For example, there is a need for more research on formulation and job opportunities. Several ingredients, various tastes, and acceptable plant-based seafood products will be available. It is important to reiterate that:

– Traditional seafood has been consumed for decades in coastal countries. According to more immigration and health concerns plant-based seafood will be accepted and consumed nearly all around the world.

– Water crisis, issues associated with global warming, the challenges of CO_2 emissions, which all cumulated to the environmental crisis have all led to the need for the (global) focus on increased sustainable food production approaches.

Competing interests

The authors declare no known competing interests.

Ethics statement

The work does not involve use of human subjects.

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