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Algae : A Source of Sustainable Global Food Supply

Abstract : Algae are gaining significant global recognition as nutrient-rich, sustainable food sources. Algae can offer solutions to contemporary challenges in food security and environmental sustainability due to their rapid growth, minimal resource demands (using non-arable land and saline water), and capacity for CO2 sequestration. Nutritionally, microalgae are exceptional, typically containing 40−70% protein by dry weight with high-quality amino acid profiles, and are major sources of omega−3 fatty acids (EPA/DHA). Macroalgae provide ample soluble dietary fiber (e.g., alginate, carrageenan), a broad spectrum of vitamins (including rare plant-based Vitamin B_{12}), and minerals, notably iodine. Beyond basic nutrition, algae are rich in bioactive compounds (e.g., phycocyanin, fucoxanthin, phlorotannins) that confer documented antioxidant and anti−inflammatory properties, and have been linked to improved cardiometabolic health (e.g., *Spirulina* has been shown to reduce total and LDL cholesterol in human trials). Despite these benefits, two critical areas require vigilance: safety and sensory acceptance. Algae can bioaccumulate heavy metals (arsenic, cadmium), and high-iodine brown seaweeds can pose a risk of thyroid dysfunction if consumed excessively. Furthermore, microalgae grown in open systems carry a risk of cyanotoxin contamination (e.g., microcystins in *Spirulina*). Sensory hurdles, including strong marine flavors and

unfamiliar colors, hinder acceptance in markets, although flavor-masking techniques and targeted marketing to health-conscious consumers are showing success. Technologically, algal ingredients are being leveraged as hydrocolloids (thickeners), protein isolates in meat analogues, and natural colorants. Future research must prioritize robust human intervention trials to confirm clinical efficacy and push for harmonized global regulatory standards to ensure product safety and quality assurance.

Keywords: Algae, Food, Protein, EPA, DHA, safety.

Introduction :

Global food systems are facing pressures from population growth, environmental degradation, and the need for more sustainable food sources. Algae, which include both macroalgae (seaweeds) and microalgae (including cyanobacteria), offer diverse compounds such as proteins, lipids (including omega-3 fatty acids), vitamins, minerals, pigments, fibers, and other bioactives (Da Silva et al., 2024; Wu et al., 2023; Tagliapietra & Clerici, 2023; Ampofo & Abbey, 2022; Babich et al., 2022;). It has long been considered for human consumption in many cultures. In recent years, their potential as sustainable, functional foods have attracted renewed attention, and it has emerged as a promising candidate owing to its fast growth rates, minimal land requirement, and capacity to produce high-value nutrients (Wu et al., 2023; Ahmed et al., 2024; Tagliapietra & Clerici, 2023). They sequester carbon dioxide and can be cultivated in non-arable areas using saline or wastewater (Wu et al., 2023). In addition to their nutritional profile, algae are highly sustainable to produce. But at the same time, safety issues (heavy metal and toxin accumulation, excessive iodine) and sensory hurdles (strong "marine" flavors, unconventional textures) also must be addressed (Salehipour-Bavarsad et al., 2024). This review highlights recent literature on the comparative nutritional profiles of edible algae with other sources, food industry applications, their health and functional effects, safety and regulatory concerns.

1. Comparative Nutritional Value: Algae, Plant, and Animal Food Sources :

The table 1 highlights **algae** as a highly promising and potentially **superior food source** due to their unique combination of nutritional value and sustainability. Algae, particularly microalgae such as *Spirulina* and *Chlorella*, stand out as a superior food source due to their exceptional nutritional density and sustainability profile. One of the most significant advantages of algae lies in their **protein density and quality**. Microalgae like *Spirulina* and *Chlorella* can contain up to **70% protein by dry weight**, offering all essential amino acids required by the human body. This protein content not only rivals but often exceeds that of traditional protein sources such as soy and animal-based foods (Yimam et al., 2024; Abdel-Wareth et al., 2024; Diaz et al., 2023; Bleakley & Hayes, 2017).

Table 1: Nutritional and sustainability comparison of algae, plant, and animal foods

Nutrients/Feature	Algae (e.g., Spirulina, Chlorella)	Plant Sources (e.g., Soy, Wheat)	Animal Sources (e.g., Meat, Egg)	References
Protein (% dry weight)	50–70% (microalgae); up to 47% (red algae)	35–40% (soy); 10–15% (wheat)	40–50% (meat); 13% (egg)	Wu et al., 2023; Diaz et al., 2023
Amino Acid Profile	All essential AAs; high BCAAs, some low in sulfur AAs	All essential AAs (soy); some limiting (wheat, rice)	All essential AAs, well-balanced	Diaz et al., 2023
Lipids (PUFAs, Omega-3)	Rich in EPA, DHA (esp. microalgae)	Low, except some seeds (ALA)	Moderate (mainly saturated, some omega-3 in fish)	Yimam et al., 2024; Abdel-Wareth et al., 2024; Bleakley & Hayes, 2017)
Fiber	High (esp. macroalgae)	High	None	Patel et al., 2021
Vitamins	A, C, D, E, K, B12 (esp. red algae)	A, C, E, K, folate (no B12)	B12, A, D, E, K	Bleakley & Hayes, 2017
Minerals	Fe, Ca, Mg, K, I (very high)	Fe, Ca, Mg, K (moderate)	Fe, Ca, Zn, P (moderate-high)	Bleakley & Hayes, 2017
Bioactive Compounds	Polyphenols, carotenoids, phycobiliproteins	Polyphenols, flavonoids	Peptides, taurine	Yimam et al., 2024
Environmental Impact	Very low land/water use, high yield	Moderate land/water use	High land/water use, GHG emissions	Ijaola et al., 2023; Patel et al., 2021

In addition to protein, algae are remarkably rich in micronutrients, providing a diverse range of minerals and vitamins essential for human health. They are particularly abundant in iron, calcium, magnesium, and iodine, as well as several vitamins, including vitamin B12 in certain species—an essential nutrient typically lacking in plant-based diets. These micronutrients are often present in higher concentrations than those found in conventional plant or animal foods, highlighting algae's potential as a dense and balanced nutritional source (Wu et al., 2023; Diaz et al., 2023)

Another key advantage of algae is their rich omega-3 fatty acid content. Algae are a primary producer of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)—two essential long-chain omega-3 fatty acids traditionally associated with fish. Because fish obtain these fatty acids through the consumption of microalgae, algae serve as a direct, sustainable, and vegetarian alternative to fish-based omega-3 sources (Yimam et al., 2024; Abdel-Wareth et al., 2024; Bleakley & Hayes, 2017).

Finally, algae possess a wide array of bioactive compounds that provide additional health benefits beyond basic nutrition. These include unique antioxidants and phytochemicals such as phycobiliproteins, polyphenols, carotenoids, and sulphated polysaccharides, which exhibit strong anti-inflammatory, antioxidant, and immunomodulatory properties. Such compounds are not commonly found in other food sources, making algae particularly valuable as a functional food ingredient with the potential to support overall health and prevent chronic diseases (Wu et al., 2023; Diaz et al., 2023; Patel et al., 2021; Yimam et al., 2024; Abdel-Wareth et al., 2024; Bleakley & Hayes, 2017).

Thus, they stand out for their exceptionally high protein concentration and complete amino acid profiles, often matching or surpassing traditional plant and animal sources in these key areas. Furthermore, algae are a significant source of beneficial Omega-3 fatty acids and Vitamin B12, micronutrients that are often challenging to obtain from typical plant-only diets. While traditional animal sources do offer well-balanced protein, but their environmental cost is significantly higher.

2. Algae Nutritional Composition: A Comprehensive Overview :

Algae are recognized for their dense nutritional profiles and potential as functional food ingredients. Their composition varies by species, environment, and processing, but they consistently offer high levels of proteins, fibers, essential fatty acids, minerals, and bioactive compounds. The table 2 summarizes the nutritional composition, key bioactive compounds, productivity, and main uses of several important algae species, highlighting their value as food and feed sources. *Arthrospira* (Spirulina) and *Chlorella vulgaris* are microalgae with very high protein content (up to 70% and 65% of dry weight, respectively), moderate carbohydrates, and low to moderate lipids. They are rich in bioactive compounds such as phycocyanin (Spirulina) and carotenoids (Chlorella), and are widely used in food supplements, snacks, and animal feed due to their high protein yield and digestibility, especially when cell walls are disrupted

(Verspreet et al., 2021; Ahmed et al., 2024). *Nannochloropsis gaditana* and *Phaeodactylum tricornutum* are notable for their high lipid content, particularly omega-3 fatty acids (EPA), making them valuable for omega-3 supplements, aquafeed, and functional foods (Rivero-Pino et al., 2025; Verspreet et al., 2021).

Among macroalgae, *Undaria pinnatifida* stands out for its high protein and vitamin content (notably B12 and C), while *Himanthalia elongata* is high in carbohydrates and fiber, with significant phenolic and fucose content, making them suitable for sea vegetable products and food supplements (Martínez-Hernández et al., 2018). *Rugulopteryx okamurae* is characterized by high lipid (omega-3) and phenolic content, with demonstrated antioxidant and bioactive peptide activity, supporting its use in functional foods and biotechnology (Rivero-Pino et al., 2025). *Palmaria palmata* and *Porphyra* spp. are valued for their high carbohydrate and vitamin B12 content, supporting their use in sea vegetables, B12 enrichment, and animal feed (Martínez-Hernández et al., 2018). These species collectively offer a range of nutritional and bioactive benefits, supporting their diverse applications in food, supplements, and biotechnology (Rivero-Pino et al., 2025; Martínez-Hernández et al., 2018; Verspreet et al., 2021; Ahmed et al., 2024).

Table 2: Nutritional profiles of representative algae species

Algae Species	Protein (% DW)	Carbohydrate (% DW)	Lipid (% DW)	Key Bioactive Compounds	Productivity	Main Uses	References
Arthrospira (Spirulina)	50–70	10–20	6–8	Phycocyanin, antioxidant peptides	High protein yield, easy digestibility	Food supplements, snacks, protein enrichment, animal feed	García-Encinas et al., 2025; Wild et al., 2018
Chlorella vulgaris	45–65	10–20	5–20	Carotenoids, antioxidant peptides	High protein, good digestibility with cell disruption	Tablets, powders, smoothies, protein enrichment, animal feed	Verspreet et al., 2021; Canelli et al., 2020
Nannochloropsis gaditana	43–50	10–15	15–28	EPA (omega-3), antioxidant peptides	High lipid productivity, especially EPA	Omega-3 supplements, aquafeed, functional foods	Hulatt et al., 2017
Phaeodactylum tricornutum	44–45	10–15	11–19	EPA, carotenoids	Moderate protein,	Functional foods,	Wild et al., 2018;

					high omega-3 content	aquafeed, Omega-3 oils	
Undaria pinnatifida	51.6	30–40	Low	Fucose, phenolics, vitamin C, B12	High protein among macroalgae	Seaweed salads, soups, food supplements, iodine/B12 source	(Martínez-Hernández et al., 2018; Cassani et al., 2022
Himanthalia elongata	~10	50–60	Low	Phenolics, fucose	High fiber, antioxidant content	Sea vegetable, fiber enrichment, antioxidant source, food supplements	Cassani et al., 2022
Rugulopteryx okamurae	14	30–35	21	Omega-3, phenolics, bioactive peptides	High lipid (omega-3), antioxidant activity	Functional foods, biotechnology, omega-3 and antioxidants source	Rivero-Pino et al., 2025
Palmaria palmata	15–25	50–55	Low	Vitamin B12, taurine	High B12, sulfonic acids	Sea vegetable, B12 enrichment, functional foods, animal feed	Martínez-Hernández et al., 2018
Porphyra spp.	25–35	40–50	Low	Vitamin B12, antioxidants	High B12, antioxidant activity	Nori sheets (sushi), B12 source, food supplements	Martínez-Hernández et al., 2018; Cassani et al., 2022

3. Health Benefits and Functional Properties :

Due to their rich composition, algae exhibit various health-promoting effects. Numerous in vitro, animal, and some human studies have documented antioxidant, anti-inflammatory, metabolic, and other functional impacts of algal components.

Antioxidant and Anti-inflammatory Effects :

Algae are rich sources of antioxidant and anti-inflammatory compounds, making them valuable as functional foods. Key bioactive molecules include carotenoids (such as fucoxanthin and lutein), phlorotannins, polyphenols, sulfated polysaccharides, and omega-3 fatty acids, all of which have demonstrated strong antioxidant activity by scavenging free radicals and reducing oxidative stress in various in vitro and in vivo models (Pagels et al., 2022; Din et al., 2022; Fernando et al., 2018; De La Fuente et al., 2020; Dong et al., 2019; Fonseca-Barahona et al., 2025; Jaworowska & Murtaza, 2022; Pei et al., 2021; Kim et al., 2023). For example, extracts from microalgae like *Tetraselmis* and *Phaeodactylum tricornutum*, as well as brown algae such as Sargassum polycystum and Cystoseira amentacea, have shown significant ability to neutralize reactive oxygen species and protect cells from oxidative damage (Pagels et al., 2022; Fernando et al., 2018; De La Fuente et al., 2020; Kim et al., 2023).

Inflammation, a driver of chronic disease, may be modulated by algal compounds. In terms of anti-inflammatory effects, algae-derived compounds can inhibit key inflammatory mediators such as nitric oxide (NO), cyclooxygenase-2 (COX-2), inducible nitric oxide synthase (iNOS), and pro-inflammatory cytokines (e.g., TNF-α, IL-6, IL-1β), often through modulation of signaling pathways like MAPK and NF-κB (Jaworowska & Murtaza, 2022; Kim et al., 2023). Notably, phlorotannins from brown algae and sulfated polysaccharides from red algae have been shown to suppress inflammation in cell and animal models, while seaweed-derived lipids (notably omega-3 PUFAs) also contribute to anti-inflammatory effects (Dong et al., 2019; Fonseca-Barahona et al., 2025; Jaworowska & Murtaza, 2022; Pei et al., 2021; Fernando et al., 2016). These properties support the use of algae as ingredients in functional foods, supplements, and nutraceuticals aimed at reducing oxidative stress and inflammation, with potential benefits for chronic disease prevention and overall health (Fonseca-Barahona et al., 2025; Pei et al., 2021).

Metabolic and Nutritional Effects :

Algae's impact on metabolism and nutrition is multifaceted. Algae are highly nutritious and offer significant metabolic benefits when consumed as food. They are rich in high-quality proteins, essential amino acids, polyunsaturated fatty acids (notably omega-3s like EPA and DHA), dietary fiber, vitamins (such as folate and B12), minerals, and a variety of bioactive compounds including carotenoids, polyphenols, and phycobiliproteins (Maghimaa et al., 2025; Tavares et al., 2023; Ahmed et al., 2024). These nutrients contribute to improved metabolic health by supporting glucose and lipid homeostasis, reducing inflammation, and providing antioxidant protection, which can help prevent or manage metabolic syndrome, obesity, diabetes, and cardiovascular diseases (Ramos-Romero et al., 2021; Wu et al., 2023).

Algae also act as prebiotics due to their polysaccharide and fiber content, promoting gut health and modulating the microbiota, which further supports metabolic regulation (Peñalver et al., 2024; Patel et al., 2021; Ahmed et al., 2024). Studies have shown that regular consumption of algae can improve blood lipid profiles, lower blood pressure, and enhance immune function, while their bioactive compounds may exert antihypertensive, antidiabetic, and anti-obesity effects (Tavares et al., 2023). Algae can help address nutritional deficiencies. For example, nori (*Porphyra*) is recognized as a natural vegan source of B_12, potentially preventing deficiency in strict vegetarians. Seaweed iodine can prevent goiter in iodine-deficient populations However, the nutritional composition and health effects can vary widely depending on the species, processing methods, and individual bioavailability, and some algae may contain undesirable compounds such as heavy metals or strong flavors that require careful management (Wells et al., 2016; Peñalver et al., 2024; Demarco et al., 2022; Wu et al., 2023). Overall, algae are considered sustainable, functional foods with the potential to address nutritional deficiencies and support metabolic health in diverse populations.

Functional Food and Bioactive Applications :

Beyond direct consumption, algae-derived ingredients are used for their functional properties. Algae-derived ingredients are widely used in the food industry for their functional and bioactive properties. Seaweed polysaccharides such as carrageenan, agar, and alginate act as hydrocolloids, providing gelling, thickening, and stabilizing functions in products like dairy, desserts, and plant-based alternatives; for example, sodium alginate is common in vegan cheese and ice cream, while carrageenan enhances gel strength in yogurts and plant milks (Kaur et al., 2024; Tagliapietra & Clerici, 2023). Algal protein isolates and flours, especially from Spirulina and Chlorella, are incorporated into shakes, bars, and meat analogues, valued for their emulsifying and foaming properties in bakery and beverage mixes (Bortolini et al., 2022; Ampofo & Abbey, 2022). Pigment extracts from algae, such as phycocyanin (blue) and astaxanthin (red), serve as natural colorants and antioxidants, while marine algae like *Schizochytrium* are commercial sources of omega-3 oils (DHA/EPA) for food fortification and vegetarian supplements (Ashaolu et al., 2021; Bortolini et al., 2022; Ampofo & Abbey, 2022)

Bioactive compounds from algae, including fucoidans, laminarin, and peptides, are marketed as nutraceuticals for immune support, wound healing, antihypertensive, and anti-aging effects (Kaur et al., 2024; Lafarga et al., 2020; Fonseca-Barahona et al., 2025). Animal and human studies have shown that red algal phycobiliproteins possess antioxidant capacity, brown algal fucans exhibit anticoagulant activity, and microalgal extracts enriched in lutein or zeaxanthin are used for eye health (Ashaolu et al., 2021; Lafarga et al., 2020; Babich et al., 2022; Din et al., 2022). While these applications are promising, the bioavailability and effective doses of these compounds—especially in whole foods versus extracts—are still under investigation, and more clinical validation is needed to confirm population-level health benefits (Ampofo & Abbey, 2022; Din et al., 2022). Overall, the combination of nutritional value and diverse bioactivities makes algae attractive for functional and medical foods, with ongoing research focused on optimizing their use and efficacy (Lafarga et al., 2020; Babich et al., 2022; Fonseca-Barahona et al., 2025; Tagliapietra & Clerici, 2023; Bortolini et al., 2022).

4. Sustainability of Production :

Algae production offers notable sustainability advantages over traditional terrestrial crops. Algae can be cultivated using seawater or wastewater, reducing competition for freshwater and arable land, and microalgae often achieve much higher areal yields of protein or oil compared to crops like soybean or rapeseed (Soudagar et al., 2024; Ubando et al., 2022; Braud et al., 2023). Algal farms can absorb CO_2 and nitrogen from effluents, helping to mitigate pollution, while marine seaweed aquaculture typically requires no fertilizers and minimal freshwater inputs (Braud et al., 2023; Zarra et al., 2024; Soudagar et al., 2024). Life cycle assessments (LCA) generally show that algae systems can have lower greenhouse gas and water footprints than livestock or some crops, especially when integrated with bioenergy production or waste stream utilization; for example, using wastewater as a nutrient source and renewable energy can reduce environmental impacts by up to 45% (Gaber et al., 2021; Kurniawan et al., 2024; Brentner et al., 2011).

However, challenges remain, including scaling up cultivation systems, ensuring energy-efficient harvesting and drying, and minimizing ecosystem impacts from large-scale monocultures (Ubando et al., 2022; Gurreri et al., 2024; Soudagar et al., 2024). Integrated approaches—such as coupling algal ponds with fish or livestock effluents, or developing biorefineries that co-produce food and fuel—are being explored to improve both economic and environmental sustainability (Ubando et al., 2022). In food technology, algae-derived hydrocolloids like alginate can extend shelf-life by absorbing moisture, and algal antioxidants are studied as natural preservatives, while research into renewable-energy-based drying methods aims to further reduce the environmental footprint (Soudagar et al., 2024). Overall, algae present multiple pathways to more sustainable and healthful food production, aligning with global sustainability goals (Kurniawan et al., 2024; Brentner et al., 2011).

5. Safety and regulatory concerns ;

Safety concerns regarding algae as food primarily involve the risk of contamination by heavy metals, toxins, and pathogenic microorganisms, as well as issues related to allergenicity and the presence of undesirable compounds. Algae can accumulate heavy metals (such as arsenic, cadmium, and lead) from their environment, especially when harvested from polluted waters, making regular monitoring and cultivation in controlled environments essential to minimize chemical risks (Cavallo et al., 2021; Cheng-Ye, 2011). Microbial contamination is another major concern, as algae can harbor bacteria, viruses, and other pathogens, necessitating rapid and accurate detection methods and strict hygiene throughout the production and supply chain (Cavallo et al., 2021). While most studies report low risks for microbiological, allergenic, and physical hazards, chemical contamination remains a significant issue, and foodborne illnesses linked to algae have been documented when safety protocols are not followed (Ampofo & Abbey, 2022).

Regulatory frameworks for algae as food are still evolving and can be inconsistent across regions. In the European Union, for example, only a small fraction of algae species are approved under the Novel Food legislation, highlighting the need for updated and harmonized regulations to ensure consumer safety and facilitate market growth (Mendes et al., 2022; Hosseinkhani et al., 2022). There are also ongoing debates about the safety of certain algae-derived food additives, such as carrageenan, which has been associated with potential pro-inflammatory effects, though other hydrocolloids like agar and alginate are generally considered safe (Liao et al., 2021). As the industry grows, comprehensive quality control, regular safety assessments, and clear regulatory guidelines are crucial to address these concerns and support the safe commercialization of algae-based foods (Liao et al., 2021; Mendes et al., 2022; U. et al., 2019).

6. Consumer Perception and Sensory Acceptability :

The most critical barrier to expanding algae consumption is its strong sensory profile, which many consumers find off-putting. The Flavor and Aroma often include intense briny, "fishy," or grassy notes, resulting from compounds like sulfur compounds (e.g., dimethyl sulfide), amines (trimethylamine), and lipid oxidation products. Some microalgae, like *Rhodomonas salina*, can even smell "crab-like," which may be desirable in products designed to mimic seafood (like plant-based salmon), but creates a significant challenge for blending into neutral foods such as baked goods or dairy analogues. Additionally, bitterness, stemming from free amino acids or algal pigments, can be detected at very low levels, necessitating the use of masking agents or strong flavor pairings, such as incorporating *Spirulina* into chocolate bars.The natural Color of algae also affects acceptance. The intense green-blue pigments (chlorophyll, phycocyanin) give foods vibrant but often unfamiliar hues that can attract a health-conscious minority but deter others who associate the color with artificiality or strangeness. The final sensory obstacle is Texture, where whole seaweeds are often enjoyed for their chewiness, but the incorporation of powdered algae into products like bread can alter the crumb structure or even create a slimy sensation if used in excess. However, Innovations like microencapsulation are being developed to retain nutritional benefits while minimizing these negative sensory impacts. Future innovations, such as fermented algal foods (which can reduce bitterness) and creative flavor-blending (using kelp for umami in broths), are key to overcoming the sensory hurdle and achieving broader market acceptance

Conclusion : Algae are poised to be a transformative component of the global food system, offering unmatched nutritional density coupled with significant sustainability advantages over conventional agriculture. The nutritional data overwhelmingly confirms their status as superfoods where microalgae provide high-quality protein and essential Omega−3 fatty acids, while macroalgae deliver unique fibers and crucial micronutrients, particularly iodine and Vitamin B12. Clinical and *in vitro* evidence supports the use of algal compounds for their functional benefits, including antioxidant activity and favorable metabolic effects on lipids and glucose control. However, Widespread adoption of algae as a food source faces two main hurdles. First, Safety and Regulation are critical: algae can accumulate heavy metals and cyanotoxins, and certain types pose a risk of iodine overdose. This demands strict quality control and harmonized global safety standards that require mandatory labeling of high-risk components. Second, Consumer Acceptance remains low due to algae's strong sensory profile (fishy smell, bitter taste, intense color). This requires continued product innovation aimed at masking the flavor by incorporating small amounts (1−5%) into familiar foods or by harnessing savory notes for specific applications like plant-based seafood analogues. Thus, algae provide a vital pathway towards a more sustainable and nutritious global food supply. Future research must now transition from documenting potential to providing robust clinical validation and driving technological solutions that ensure safety and universal palatability.

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