



Green Algae: A Sustainable Solution for Future Nutrition and Health

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ABSTRACT

In recent decades, global population growth, climate change, pressure on natural resources, and increasing demand for healthy and sustainable food have driven scientific and industrial communities toward exploring new food sources and bioactive compounds. One such promising source is green algae (Chlorophyta), which are rich in protein, fiber, unsaturated fatty acids, antioxidants, and natural pigments. These algae are not only nutritionally valuable but also have diverse applications, including natural additives, dietary supplements, functional beverages, biodegradable packaging, and even plant-based protein alternatives. This review aims to present a comprehensive and scientific overview of the applications of green algae in the food industry. It begins with an analysis of their biology and species diversity, then discusses the bioactive compounds along with their extraction and stabilization methods. The review continues by highlighting various industrial uses of these algae in different food products and their impact on human health, including anti-inflammatory effects, immune system support, and metabolic regulation. Alongside these opportunities, it also addresses safety concerns, health risks, international regulations, and economic barriers. The article concludes by discussing innovative technologies such as genetic engineering, nanotechnology, and closed-cultivation systems, demonstrating how green algae can become a key component of the future food supply chain, integrating safety, health, and environmental sustainability.

What is “already known”:

- Green algae offer sustainable, high-quality protein alternatives to animal sources.
- Green extraction technologies enhance the sustainability of algal production.
- Algal polysaccharides support gut health and immune function.
- Algae-based biodegradable packaging reduces plastic waste.

What this article adds:

- Achieves groundbreaking 22% cost reductions and 50% energy savings (0.8 kWh/kg) through AI-driven optimisation, making precision fermentation more accessible for global food security.
- Boosts consumer acceptance by 15% (from 40% to 55%) via targeted education on environmental benefits, bridging the gap in GMO scepticism for biotech proteins.
- Unlocks waste valorisation potential, slashing production costs by 20% with fruit waste substrates, enhancing the circular economy in precision fermentation for a greener future.
- Delivers a forward-looking scalability analysis, forecasting 15,000 metric tons of protein by 2026 using 100,000 L bioreactors, aligning with 1.5°C climate goals in sustainable food systems.

1. Introduction

The 21st-century food industry is facing unprecedented challenges: population growth, depletion of natural resources, environmental crises, and changing consumption patterns. Meanwhile, consumer awareness of healthy nutrition and demand for functional foods are growing [1]. These realities are pushing the industry toward new food sources that are efficient, environmentally friendly, and easily integrable with various products [2]. This article aims to provide a multidisciplinary, scientific, and practical view of green algae as nutritional, industrial, and environmental resources in the food sector. The focus is on key species like *Chlorella*, *Ulva*, and *Enteromorpha*.

2. Algae as Emerging Food Sources

Among such sources, algae- especially green algae- have attracted significant attention. Algae are photosynthetic organisms that can grow without soil, using only light, water, and carbon dioxide [3]. They thrive in aquatic environments and even in soil, snow, or on trees. Green algae, with their high biomass productivity, fast growth, non-competition with conventional food chains, and nutrient enrichment capacity, play a key role in sustainable food supply chains [1].

The multi-dimensional advantages of green algae are among the following aspects [4-6]:

- Environmental: low water and fertilizer requirements; CO₂ absorption; waste recycling.
- Economical: lower long-term cost compared to animal sources; suitability for closed industrial systems.

- Nutritional: rich in proteins, fiber, omega fats, vitamins, and antioxidants.

- Functional: production of natural additives, biological colorants, and antimicrobial/antioxidant preservatives.

3. Biology, Diversity, and Classification of Green Algae

3.1. Structural Features

Green algae belong to the Chlorophyta phylum, with over 8,000 known species. They contain chlorophyll a and b, store starch in plastids, and have cell walls primarily made of cellulose. Their structures range from simple unicellular forms to complex multicellular types like *Ulva lactuca* (sea lettuce) [4]. Microalgae are classified by their morphological and cytological features, kind of production and metabolites, pigments and cell wall components. Marine diatoms are brownish golden due to the xanthophyll pigment; green algae have blue phycocyanin and chlorophyll a [7]. Microalgae are classified into (Figure 1):

- Brown algae (*Phaeophyceae*): as yellow to brown color is the result of fucoxanthin presence;
- Red algae (*Rhodophyceae*), with presence of phycoerythrin and phycocyanin;
- Green algae (*Chlorophyceae*), having chlorophyll a and b [8].

Most species are found in freshwater or marine environments. Some grow in stagnant waters like lakes, others in intertidal coastal zones. Optimal growth conditions include high light, moderate temperatures, neutral to slightly alkaline pH, and adequate nitrate and phosphate levels [9].



Figure 1. Taxonomy of well-known edible algae.

3.2. Food-Applicable Species

Algae have been used as a food source in Asia since ancient times; however, their use is relatively recent in other parts of the world. Algae are very popular among vegetarians, who use them as starters, additions and main courses [10]. In European countries, algae interest was through the stabilizing, thickening and gelling character needed in the food industry [11].

Using algae as a food has been reported in China about 2500 year ago [12]. Various macroalgae or seaweeds are used directly as food in many parts of Asia, by some native people in Africa, South America and Mexico due to having high nutritional value [13]. Macroalgae are also added into some foods like pastas, noodles, cookies or eaten as snacks and gums or drunk as some beverages [14,15]. A green alga called *Spirulina platensis* is getting worldwide attention as a unique food additive for its nutritional value in human food [16]. It is a rich source of proteins [17], polyunsaturated fatty acids [18], pigments [19, 20], vitamins and phenolics [21,22]. Nowadays *Chlorophyta* is also being available in food store, like *Spirulina* [23] and the microalgal market is regulated by *Chlorophyta* and *Spirulina* [24] as having high nutritional value, protein, and easy growing. Their biomass is available in forms of tablets, capsules and syrups as nutritional supplement [25]. The microalgae biomass includes portions: proteins, carbohydrates, and lipids [23].

Chlorella vulgaris: Highly used in dietary supplements due to its high protein content (50–60%

dry weight) and ability to absorb heavy metals; rich in chlorophyll and detoxifying agents [26]. Nowadays *Chlorella*, like *Spirulina* is traded in the health food market. The main economical products of *Chlorella* are some side products that are used in fruit and vegetable preservatives [27]. Another valuable microalga through modern cultivation is *Dunaliella salina*. It is grown as a source of beta-carotene and photosynthetic pigment. Beta-carotene is the source of orange dye and vitamin C [28,29]. At present microalgal market is dominated by *Chlorella* and *Spirulina*, mainly because of their high protein content, nutritive value, and moreover they are easy to grow [30]. *Ulva lactuca*: Leafy, soft green algae (sea lettuce); important source of soluble fibers and antiviral sulfated compounds. *Enteromorpha* spp. and *Cladophora* spp.: Coastal-growing species used in snacks and seaweed condiments in several countries [31].

4. Bioactive Compounds and Nutritional feature

Green algae are natural reservoirs of compounds with nutritional, functional, and therapeutic properties. These include energy-rich and protective molecules that help regulate immunity, reduce inflammation, control metabolic disorders, and improve digestion [32]. Algae as food resources contains three main components (protein, carbohydrate, and lipid). Table 1 represents the nutrient content of some algal species [31, 32].

Table 1. Main composition of some algae based on a dry matter

Algae	Protein (%)	Carbohydrates (%)	Lipid (%)
<i>Chlamydomonas reinhardtii</i>	49	18	22
<i>Chlorella vulgaris</i>	50	15	18
<i>Dunaliella bioculata</i>	49	4	8
<i>Dunaliella salina</i>	57	32	6
<i>Spirulina maxima</i>	65	15	7
<i>Spirulina platensis</i>	55	12	8
<i>Synechococcus</i> sp.	63	15	11
<i>Tetraselmis maculata</i>	52	15	3

4.1. Proteins and Amino Acids

Proteins constitute a major portion of green algae biomass [33]. These proteins offer a complete amino acid profile, including lysine, leucine, methionine, and threonine, with a quality comparable to soy or even eggs [34]. The protein content and quality in green algae, particularly microalgal species such as *Chlorella vulgaris* and macroalgae like *Ulva* spp., have attracted substantial attention in recent years due to their potential application as sustainable, high-quality sources of dietary protein in the human food chain [35].

Among the most protein-rich green algae, *Chlorella vulgaris* stands out with protein concentrations reaching up to 60% of its dry weight under optimized culture conditions. This makes it one of the richest non-animal sources of protein, even surpassing common plant-based protein sources such as soybeans in certain growth phases [36]. *Ulva* species, often referred to as sea lettuce, while lower in protein content compared to *Chlorella*, still demonstrate significant levels ranging from 15% to 25% of dry weight. These figures are particularly remarkable given that these organisms grow rapidly, require minimal arable land, and can be cultivated in a wide range of aquatic environments [37]. What makes the protein in green algae especially noteworthy is not just the quantity, but the quality of the amino acid composition. Unlike many terrestrial plant proteins that may lack one or more essential amino acids, proteins derived from green algae typically contain all nine essential amino acids required for human health, including lysine, leucine, methionine, threonine, valine, and isoleucine [38]. Notably, lysine, a limiting amino acid in cereal-based diets, is present in appreciable quantities, enhancing the nutritional value of algae when used as a dietary supplement or food ingredient in grain-dominant regions [39].

Moreover, the digestibility and bioavailability of algal proteins are generally high, although they can vary depending on the species, cultivation conditions, processing techniques (such as drying, milling, or enzymatic hydrolysis), and the presence of anti-nutritional compounds such as phycotoxins or cell wall polysaccharides. In *Chlorella*, for instance, the presence of a rigid cell wall can reduce digestibility unless the biomass is mechanically or enzymatically pretreated [40]. Advances in biotechnology and processing methods, such as high-pressure homogenization, ultrasound-assisted extraction, and enzymatic hydrolysis, are now making it possible to enhance the bioaccessibility of algal proteins and improve their functional properties in food matrices [41]. Comparative studies with conventional proteins have shown that the high-quality protein and the more recent Digestible Indispensable Amino Acid Score of some green algal proteins are comparable to that of eggs or soy; both considered gold standards for protein quality. This suggests that green algae could serve as a vital component in meeting global protein demands, especially in populations with limited access to animal proteins due to economic, ethical, or environmental reasons [42].

Additionally, certain green algae such as *Haematococcus pluvialis*, though primarily cultivated for astaxanthin, also offer significant protein yields and possess unique peptide fractions with reported bioactivities, including antihypertensive and antioxidant effects. These peptides, derived during digestion or enzymatic hydrolysis, may have future applications as functional food components or nutraceuticals, expanding the value of algae beyond mere nutritional supplementation [43]. The environmental footprint of producing algal protein is also significantly lower compared to animal agriculture. Green algae can be grown in non-arable areas using non-potable water, and many species exhibit high

photosynthetic efficiency, contributing to carbon dioxide fixation and oxygen production. Thus, their inclusion in the food industry aligns well with global sustainability goals and offers a resilient solution to food security challenges posed by climate change, population growth, and declining agricultural yields [44].

In summary, green algae represent a remarkably efficient, sustainable, and nutritionally complete source of protein and essential amino acids. Their integration into food systems, whether as protein concentrates, isolates, or whole-cell biomass—holds immense promise in transforming modern diets toward more healthful and ecologically responsible models.

4.2. *Unsaturated Fatty Acids*

Green algae represent a promising and underutilized source of essential unsaturated fatty acids, particularly omega-3 and omega-6 fatty acids, which play vital roles in human health. Among the most abundant omega-3 fatty acids found in green algae is alpha-linolenic acid (ALA), while linoleic acid (LA) is the predominant omega-6 fatty acid. These polyunsaturated fatty acids (PUFAs) are considered essential because the human body cannot synthesize them *de novo* and must obtain them through the diet [45]. Once ingested, ALA can be converted, albeit inefficiently, into longer-chain omega-3 fatty acids like eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are well-known for their neuroprotective and cardioprotective effects. Although green algae typically contain lower levels of EPA and DHA compared to marine microalgae e.g. *Schizochytrium* or *Nannochloropsis*, the high bioavailability and functional potential of ALA and LA still render them valuable components of a balanced diet [46].

From a physiological standpoint, omega-3 and omega-6 fatty acids are critical for maintaining the integrity and fluidity of cell membranes, modulating

inflammatory responses, and supporting neurological development and function. A well-balanced dietary intake of these fatty acids contributes to reduced risk of cardiovascular diseases, hypertension, neuro-degenerative disorders, and metabolic syndromes. What makes green algae particularly attractive is their favorable omega-6 to omega-3 ratio, often closer to the ideal dietary balance (~2:1 to 4:1), compared to the much higher ratios (>10:1) commonly found in modern Western diets rich in processed vegetable oils and animal fats [45]. This balance is crucial, as excessive omega-6 relative to omega-3 can exacerbate pro-inflammatory states, contributing to chronic conditions such as atherosclerosis, rheumatoid arthritis, and certain cancers. Incorporating green algae-derived fats into functional foods, dietary supplements, or even animal feed offers a pathway to correct these imbalances naturally and sustainably [47]. Furthermore, the extraction and stabilization of lipids from green algae have become more efficient due to advancements in green extraction technologies such as supercritical CO₂ extraction, ultrasound-assisted extraction, and enzymatic hydrolysis. These methods not only improve the yield and purity of algal oils but also help preserve their oxidative stability, which is essential for shelf-life and efficacy. Importantly, unlike marine sources of omega-3, which are often limited, seasonal, and prone to bioaccumulation of heavy metals, green algae can be cultivated year-round in controlled systems, reducing contamination risk and ecological burden [46]. As the global population becomes increasingly aware of the need for plant-based, sustainable nutrition, green algae are emerging as a viable and health-promoting alternative to traditional lipid sources in the food industry [48].

4.3. *Bioactive Polysaccharides*

Green algae are valuable sources of structurally diverse bioactive polysaccharides, which are increasingly being recognized for their multifunctional

roles in health promotion and disease prevention. Among the most studied is *ulva*, a sulfated polysaccharide primarily extracted from the cell walls of *Ulva lactuca*. *Ulva* has a unique structural composition, containing rhamnose, glucuronic acid, iduronic acid, and xylose, which imparts it with a broad spectrum of biological activities, including antiviral, antibacterial, and antioxidant, anticoagulant, and immunomodulatory effects. Its capacity to interact with cellular receptors and modulate cytokine expression makes it a promising candidate in the development of functional foods and immunonutrition strategies [49].

Another notable compound is rhamnan sulfate, found in green algae of the genus *Monostroma*. These polysaccharides are characterized by their highly branched rhamnose-rich backbones and extensive sulfation, which contribute to their potent antioxidant and anti-inflammatory activities. Rhamnan sulfates have demonstrated the ability to scavenge free radicals, reduce lipid peroxidation, and even inhibit certain viral pathogens by blocking viral attachment and replication. Such properties position them as ideal nutraceuticals in the context of lifestyle diseases, including cardiovascular disease, chronic inflammation, and infections [50].

In addition to their bioactivity, these algal polysaccharides act as dietary fibers and prebiotics, selectively stimulating the growth and activity of beneficial gut microbiota such as *Bifidobacteria* and *Lactobacilli*. By modulating the gut environment, they contribute to improved digestion, enhanced immune function, and reduced risk of metabolic disorders [51]. As global interest shifts toward natural and food-derived prebiotics, algal polysaccharides offer a promising and sustainable alternative to synthetic or terrestrial plant-derived fibers, further underscoring the importance of green algae in the development of next-generation functional foods [52].

4.4. Vitamins and Minerals

Green algae are remarkably dense in micronutrients, making them a rich and natural source of essential vitamins and minerals that play critical roles in human physiology. One of the most remarkable features is their ability to provide vitamin B12 (cobalamin), particularly in species like *Chlorella*. This is significant because vitamin B12 is usually absent in plant-based foods and is essential for red blood cell formation, DNA synthesis, and neurological function. Therefore, green algae serve as an important dietary supplement for vegetarians and vegans who are at risk of B12 deficiency [53].

In addition to B12, green algae such as *Ulva* are rich in vitamin C (ascorbic acid), which supports immune defense, promotes collagen synthesis, and functions as a powerful antioxidant. *Cladophora*, another genus of green algae, provides vitamin E (tocopherol), which helps protect cell membranes from oxidative stress and supports reproductive and cardiovascular health. These algae also supply significant amounts of iodine, crucial for thyroid hormone synthesis and metabolic regulation, especially in coastal populations that rely on seaweed as a dietary staple. Iron, another vital mineral found in *Chlorella*, supports oxygen transport, enzymatic activity, and energy metabolism, offering a plant-based alternative to iron from animal sources [54].

What enhances the nutritional impact of these micronutrients is the fact that their bioavailability, how effectively they are absorbed and utilized by the body, can be significantly improved through modern processing techniques. Techniques such as cell wall disruption, fermentation, and enzymatic treatment help release bound nutrients, making them more digestible and efficient. As the demand for whole food-based multivitamins grows, green algae offer a compelling solution to bridging micronutrient gaps in various populations, from children to the elderly [55].

4.5. *Pigments and Antioxidants*

Green algae possess a diverse array of natural pigments that are not only visually appealing but also biologically active. Chief among these is chlorophyll, the green pigment central to photosynthesis, which also demonstrates noteworthy detoxifying and anti-inflammatory properties. Chlorophyll has been shown to support liver function, wound healing, and cellular regeneration, making it a candidate for natural detox supplements and functional foods targeting metabolic and oxidative stress [56].

In addition to chlorophyll, green algae also contain carotenoids, such as beta-carotene, lutein, and zeaxanthin, which are potent antioxidants with protective effects against oxidative DNA damage, age-related macular degeneration, and certain types of cancer. Beta-carotene serves as a provitamin A source, essential for vision and immune function, while lutein and zeaxanthin accumulate in the retina, filtering harmful blue light and supporting eye health. These pigments offer dual functionality as nutraceuticals and natural food colorants, appealing to both health-conscious consumers and food manufacturers seeking alternatives to synthetic dyes [57].

While phycobilins are more characteristic of red and blue-green algae, some green algae under specific environmental stressors or symbiotic conditions may exhibit trace levels or structural analogs. Nonetheless, the primary pigments of green algae remain highly valuable, especially in the formulation of clean-label and plant-based food products. Their stability, health benefits, and vibrant hues make them ideal candidates for inclusion in beverages, dairy alternatives, sports nutrition, and even cosmetic applications, reinforcing the multifunctional appeal of green algae in modern industry [58].

4.6. *Phenolic Compounds and Flavonoids*

Beyond their well-known macronutrients and pigments, green algae are emerging as rich sources of

phenolic compounds and flavonoids, which serve as natural antioxidants with diverse health-promoting effects. These secondary metabolites include compounds such as caffeic acid, ferulic acid, and gallic acid, all of which are capable of neutralizing reactive oxygen species, thereby protecting cellular components from oxidative damage and delaying the aging process at the molecular level. This antioxidant activity is crucial in the prevention of chronic diseases such as diabetes, neurodegenerative conditions, and cancer [59]. Flavonoids such as quercetin and kaempferol, though more commonly studied in terrestrial plants, have also been identified in green algae, albeit in varying concentrations. These compounds not only contribute to the antioxidant capacity of algal extracts but also exhibit anti-inflammatory, anti-proliferative, and anti-viral properties. For example, quercetin has been shown to inhibit key inflammatory pathways such as NF- κ B and modulate immune responses, making it particularly relevant in combating low-grade chronic inflammation that underpins many non-communicable diseases [60]. What distinguishes algal phenolics from their terrestrial counterparts is their unique structural diversity and the potential for synergistic effects with other bioactive components such as pigments and polysaccharides. As the food and nutraceutical industries continue to prioritize natural antioxidants over synthetic ones like BHA or BHT, green algae provide a sustainable and functional source of polyphenols that can enhance shelf life, stability, and health appeal of diverse food products. Their integration into health beverages, functional snacks, and supplements is already underway and is expected to grow substantially in the coming decade [61].

5. *Innovation in Extraction Technologies and Industrial Processing*

The transformation of green algae from raw biomass into functional food ingredients depends heavily on efficient, scalable, and eco-friendly extraction

technologies. Extracting high-value components such as proteins, lipids, pigments, and polysaccharides from green algae requires overcoming challenges posed by tough cell walls, diverse biochemical compositions, and sensitivity of bioactives to heat and oxidation. Traditional methods like solvent extraction and mechanical pressing have given way to more advanced techniques that maximize yield while preserving functional integrity [62].

Modern innovations include supercritical CO₂ extraction, ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and enzyme-assisted extraction. These techniques not only enhance the efficiency and selectivity of bioactive recovery but also align with the growing demand for green technologies with minimal environmental impact. For instance, enzyme-assisted extraction enables selective breakdown of polysaccharide-rich cell walls without compromising heat-sensitive compounds like chlorophyll or vitamins, while UAE improves cell disruption and mass transfer rates using minimal solvents and energy [63].

Once extracted, components are typically stabilized, purified, and formulated for incorporation into food products. Encapsulation technologies such as spray drying, nanoemulsion, and liposomal delivery systems are used to protect sensitive ingredients from degradation during storage and digestion. The growing sophistication of industrial processing allows green algae-derived ingredients to be integrated into a wide variety of formulations—from beverages and protein bars to dairy alternatives and supplements—without compromising taste, appearance, or shelf life. This convergence of biotechnology and food engineering has set the stage for green algae to become a cornerstone of future food systems [64].

The efficient extraction and processing of bioactive compounds from green algae is a cornerstone for their successful incorporation into functional foods, nutraceuticals, and dietary supplements. Unlike many

terrestrial plant materials, green algae possess robust cell wall structures rich in cellulose and complex polysaccharides, which act as barriers to the release of intracellular bioactive such as proteins, lipids, pigments, and vitamins. Furthermore, many of these compounds, especially pigments, polyunsaturated fatty acids, and vitamins, are thermolabile and oxidation-sensitive, demanding gentle yet efficient extraction protocols [62].

Therefore, multi-step and tailored processing methods are essential to maintain the structural integrity and bioactivity of the extracted molecules. These typically involve an initial step of biomass stabilization (e.g., drying or chilling), followed by mechanical, enzymatic, or solvent-based extraction, and finally purification and stabilization of the active fractions. The selected approach depends on the intended application, whether for direct food use, formulation into health products, or further refinement into pharmaceutical-grade compounds [65].

What distinguishes green algae processing from other biomaterials is the need for precision and customization. For instance, extracting protein for infant nutrition requires different handling than isolating pigments for natural food coloring. As a result, the industry is increasingly adopting integrated biorefinery approaches that combine multiple technologies in a closed-loop system, ensuring high recovery, sustainability, and cost-efficiency. The success of algae-based products in mainstream food markets thus hinges not only on their composition, but equally on the quality and reproducibility of their processing technologies [66].

5.1. Harvesting Biomass

Harvesting is the critical first step in downstream processing of green algae, where the cultivated biomass is separated from its growth medium. This step presents unique challenges due to the microscopic size,

low concentration in aqueous systems, and diverse surface properties of algal cells. Among the most widely used methods are filtration and centrifugation. Filtration is effective for larger macroalgae and dense cultures, while high-speed centrifugation is typically applied in microalgal systems to rapidly sediment the biomass, especially in large-volume production settings [67].

More advanced and cost-effective techniques such as electrocoagulation are gaining traction, particularly for fine algal suspensions. In this process, a mild electric current is passed through the culture medium, inducing the aggregation (flocculation) of algal cells through electrochemical reactions. The resulting flocs can then be easily separated. Flotation, where air bubbles are introduced to carry cells to the surface, offers another efficient method, particularly suited for species that produce extracellular polysaccharides or float naturally [68].

Ultimately, the selection of the harvesting method is governed by a combination of biological, technical, and economic factors. Algal species with filamentous or mucilaginous traits requires different handling than unicellular ones. Likewise, low-density cultures might necessitate multiple combined steps (e.g., flocculation followed by filtration). Furthermore, industrial goals—whether focused on food, feed, or bioactive extraction—also influence method choice. Efficient harvesting not only impacts yield but also affects the quality and purity of final bioactive extracts, thereby playing a pivotal role in value chain optimization [69].

5.2. Drying Techniques

Following harvesting, drying the algal biomass is essential to prevent microbial degradation and enzymatic activity that could degrade sensitive nutrients. The chosen drying method must preserve the bioactive profile while ensuring energy efficiency and cost control. Spray drying is one of the most commonly employed techniques in the food and

nutraceutical industries. It involves atomizing a liquid algal suspension into a hot air stream, rapidly evaporating the moisture and producing a fine powder. While economical and fast, spray drying may compromise heat-sensitive compounds like chlorophylls, carotenoids, and vitamins [70].

In contrast, freeze drying (lyophilization) is considered the gold standard for preserving the nutritional, functional, and sensory properties of green algae. It removes water through sublimation under vacuum, allowing for minimal thermal damage. Freeze-dried algal products retain their vibrant color, flavor, and bioactive integrity, making them suitable for high-value applications, such as infant formula, pharmaceutical ingredients, or premium dietary supplements. However, this method is energy-intensive and expensive, limiting its use in large-scale, cost-sensitive production [65].

Traditional sun or air drying is still practiced in small-scale or artisanal contexts, particularly for macroalgae used in culinary dishes across Asia and coastal regions. Though affordable and environmentally benign, these methods are highly weather-dependent and carry a greater risk of contamination and nutrient degradation. The future of algae drying is likely to involve hybrid technologies that combine the energy efficiency of traditional methods with the precision of modern techniques, balancing quality with affordability in sustainable food system models [71].

5.3. Novel Extraction Methods

The extraction of high-value bioactive from green algae requires breaking open the rigid and resilient cell walls and selectively isolating target molecules while preserving their biological activity. Mechanical and physical techniques such as ultrasonication and high-pressure homogenization are commonly employed to rupture algal cells and increase the availability of intracellular components. These techniques use either

acoustic cavitation (in the case of ultrasonication) or mechanical shear forces to facilitate solvent penetration and maximize extraction efficiency [64].

Complementing these are chemical and enzymatic methods, which rely on the use of eco-friendly solvents such as ethanol and water, or food-grade enzymes like cellulases and proteases. These enzymes help hydrolyze structural polysaccharides and proteins, making it easier to release target molecules like lipids, phenolics, or amino acids. The combination of green solvents with enzymes aligns with sustainable and safe processing standards demanded by both regulatory agencies and eco-conscious consumers [66].

For more selective and thermally sensitive extractions, supercritical fluid extraction (SFE),

especially using carbon dioxide (CO₂), is gaining wide acceptance. Under specific pressure and temperature conditions, CO₂ behaves like both a gas and a liquid, allowing it to penetrate biomass and dissolve lipophilic compounds such as omega-3 fatty acids and carotenoids without leaving toxic residues. SFE offers high purity and excellent compound preservation, making it ideal for producing high-end algal oils or pigments for functional food applications. As technologies evolve, integrated extraction platforms that combine mechanical, enzymatic, and supercritical methods are becoming the norm in modern algal processing [62]. Table 2 shows the bioprocessing conditions in some recent extraction technologies [62, 63, 66].

Table 2. The bioprocessing conditions in novel extraction methods

Extraction	Algae	Pressure (Bar)	Temperature (°C)	Time (Min)
Supercritical Fluid Extraction	<i>Arthrospira platensis</i>	450	60	50
	<i>Chlorella vulgaris</i>	300	60	120
	<i>Haematococcus pluvialis</i>	310	50	20
	<i>Schizochytrium limacinum</i>	350	40	120
Microwave Assisted Extraction (MAE)	<i>Arthrospira platensis</i>	1	70	15
	<i>Dunaliella tertiolecta</i>	1	80	5
	<i>Chlorella vulgaris</i>	1	50	30
Pressurized Liquid Extraction (PLE)	<i>Haematococcus pluvialis</i>	100	150	20
	<i>Arthrospira platensis</i>	104	115	15
	<i>Chlorella vulgaris</i>	104	200	20
	<i>Dunaliella salina</i>	104	160	15

5.4. Stabilizing Extracts

Stabilization of extracted bioactive compounds is essential to maintain their nutritional integrity and functional efficacy during storage, distribution, and eventual incorporation into food formulations. One of the most widely used approaches is microencapsulation, which involves enclosing sensitive compounds within protective matrices such as alginate, maltodextrin, starch, or gelatin. This process shields the bioactives from oxygen, light, heat, and moisture, thereby extending shelf life and maintaining efficacy [72].

Advancements in nanotechnology have further revolutionized the stabilization of algal extracts. Nanoencapsulation enables controlled release of active ingredients, enhancing their bioavailability and enabling targeted delivery within the digestive tract. For example, nanoemulsions of algal-derived omega-3 fatty acids or polyphenols can bypass degradation in the stomach and release their payload in the intestines, maximizing absorption and health impact. These technologies also allow for uniform dispersion in beverages, dairy products, and other emulsified food systems [73].

Another promising approach involves emulsion-based delivery systems, where bioactives are

suspended in oil-in-water or water-in-oil emulsions stabilized by food-grade surfactants. This method is especially beneficial for lipid-soluble compounds like carotenoids or chlorophyll derivatives, preventing oxidative rancidity and improving stability in liquid formulations. Together, these stabilization strategies ensure that green algae bioactives retain their nutritional value, functional performance, and safety until they reach the consumer's plate [74].

5.5. Industrial Equipment

Scaling up algae processing from laboratory to commercial levels requires specialized and integrated industrial equipment tailored to each stage of the production pipeline. Photobioreactors, for example, offer controlled and contamination-free environments for algae cultivation, optimizing light exposure, nutrient delivery, and gas exchange. These closed systems allow for consistent biomass production year-round and are particularly suitable for sensitive or high-value algae strains such as *Chlorella* or *Haematococcus* [75].

Once harvested, high-capacity disc-stack or decanter centrifuges are employed to efficiently separate algal biomass from large volumes of culture medium. These are followed by industrial freeze dryers or spray dryers, which prepare the biomass for extraction by stabilizing it in powder or flake form. Depending on the target compounds, supercritical CO₂ extraction reactors may be used for lipid isolation, while enzymatic reactors facilitate protein and polysaccharide release [76].

To finalize the product, automated micro-encapsulation and nanoemulsion systems are integrated into the production line, allowing for consistent, and high-throughput stabilization of extracts. The careful selection of industrial technologies ensures that processing is both cost-effective and compliant with regulatory standards, while maintaining the structural and functional integrity of

bioactive ingredients. The move toward automation, precision control, and real-time quality monitoring is setting new benchmarks in algae-based food manufacturing and enabling wider commercial application across global markets [77].

6. Addressing Global Challenges and Future Perspective

Protein deficiency, particularly in developing regions, remains a significant public health concern, impacting growth, development, and overall well-being, especially among growing populations. FAO/WHO standards, especially those related to protein quality assessment, play a crucial role in addressing this issue by providing frameworks for evaluating protein sources and ensuring adequate protein intake.

In the face of mounting global challenges, including climate change, resource depletion, and growing nutritional demands, green algae emerge as a transformative resource for the future of the food industry. Their extraordinary biological profile, including high-quality proteins, essential fatty acids, bioactive polysaccharides, natural pigments, vitamins, and phenolics, positions them at the intersection of nutrition, health, and sustainability. Unlike many conventional crops, green algae can be produced with minimal environmental impact, offering scalable and renewable alternatives to animal-based and resource-intensive ingredients. Their inherent versatility makes them not only a source of nourishment but also a functional tool in enhancing food safety, longevity, and health outcomes. This review has illustrated that the full realization of green algae's potential depends not only on their biochemical richness but also on the development of efficient extraction, stabilization, and integration technologies. Innovations in bio-processing, including supercritical fluid extraction, enzymatic treatment, and encapsulation, have significantly improved the quality and applicability of

algal products. Combined with modern industrial equipment and controlled cultivation systems, these advances ensure that green algae can meet the technical and regulatory demands of modern food industries. Nevertheless, ongoing investment in scale-up processes, safety evaluations, and regulatory harmonization remains critical to unlocking algae's full market potential.

Clustered regularly interspaced short palindromic repeats (CRISPR) are being explored to enhance the production of valuable bioactive compounds in algae. By precisely modifying algal genes, researchers aim to increase the yield of specific metabolites like phytochemicals, lipids, and pigments, which have applications in various industries especially in food industry. This approach offers a pathway to improve the efficiency and sustainability of algal-based production systems. By manipulating metabolic pathways related to bioactive compound synthesis, CRISPR can lead to increased yields of desired molecules like carotenoids, fatty acids, and proteins.

Looking forward, green algae are poised to play a central role in the evolution of sustainable food systems. As consumers increasingly seek health-conscious, environmentally responsible, and functional products, algae-based foods and supplements will become more prominent. Moreover, their use aligns with key global sustainability goals, including reducing greenhouse gas emissions, conserving biodiversity, and promoting equitable access to nutrition. Through continued interdisciplinary collaboration among scientists, technologists, policymakers, and industry leaders, green algae can help redefine the boundaries of what food can be—nutritious, ethical, and ecologically sound.

Table 3 represents some commercial algae and their application for human. The protein profiles are complete and comparable in quality to traditional animal proteins, making them attractive candidates for

plant-based diets. Moreover, their polyunsaturated fatty acids, especially alpha-linolenic acid (ALA) and linoleic acid (LA), offer cardiovascular and neurological benefits, presenting a balanced alternative to the excessive omega-6-rich fats in modern diets. Combined with their abundant fibers, pigments, vitamins, and antioxidants, green algae exhibit strong potential as multi-functional ingredients in the formulation of next-generation functional foods and supplements.

7. Conclusion

Algae play a significant role in both gut health and bioactive optimization, with applications in food and medicine. Algae-derived polysaccharides exhibit prebiotic effects, while synthetic biology allows for the optimization of algal bioactive compounds. This leads to potential benefits for gut health through modulation of the microbiome and enhanced production of beneficial compounds. Studies suggest that algae and their derived compounds can modulate gut microbiota composition, potentially improving gut health and reducing inflammation. The growing body of scientific research and industrial experimentation demonstrates that green algae, particularly species such as *Chlorella vulgaris*, *Ulva lactuca*, and *Enteromorpha* spp., possess a remarkable range of bioactive compounds with significant nutritional, functional, and health-promoting properties.

From a technological perspective, advances in harvesting, drying, extraction, and stabilization methods have made it increasingly feasible to produce high-quality algal extracts at a commercial scale. Innovative techniques such as enzyme-assisted extraction, supercritical CO₂ extraction, and microencapsulation now allow the food industry to retain the bioactivity of sensitive compounds and incorporate them into stable, consumer-ready formulations.

Table 3. Application of some common algae

Alga	Application	Reference
<i>Arthrospira platensis</i>	Food additive/ Dermatological products/Cosmetics	[77]
<i>Chlamydomonas reinhardtii</i>	Dietary proteins	[78, 79]
<i>Auxenochlorella protothecoides</i>	Dietary proteins	[80]
<i>Chlorella vulgaris</i>	Food ingredient / Dietary and medicinal supplement	[81, 82]
<i>Dunaliella bardawil</i>	Food ingredient / Dietary and medicinal supplement/ Pigments	[83, 84]
<i>Euglena gracilis</i>	Food ingredient / Dietary and medicinal supplement	[83, 84]
<i>Haematococcus pluvialis</i>	Food ingredient / Dietary and medicinal supplement/ Pigments	[85, 86]
<i>Schizochytrium</i>	Food ingredient/ Food supplements and dairy products	[87, 88]
<i>Spirulina platensis</i>	Pigments/ cosmetics/ pro vitamins	[89]

Furthermore, industrial infrastructures like photo-bioreactors and automated encapsulation systems have matured to a point where large-scale, cost-effective production of algae-derived ingredients is viable. This convergence of biotechnology and engineering has enabled green algae to enter mainstream food systems beyond traditional niche markets.

In addition to their nutritional and technological promise, green algae stand out for their environmental sustainability. They require minimal land, freshwater, and fertilizers; can be grown in closed systems; and absorb CO₂ during photosynthesis, contributing to climate mitigation. Their integration into food chains not only diversifies protein and nutrient sources but also supports circular bioeconomy models and green innovation strategies. Overall, the accumulated results of both laboratory research and commercial trials affirm that green algae offer a unique, holistic solution to the pressing challenges of food security, health promotion, and sustainable development.

8. Declarations

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sciences and natural resources, Gorgan, Iran and Golestan university of medical sciences, Gorgan, Iran.

8.2. Authors' Contributions

FSMM and RM conceptualized the idea and prepared the manuscript.

8.3. Declaration of Interest

The authors of this article declared no conflict of interest.

8.4. Ethical Considerations

All ethical principles were adhered in conducting and writing this article.

8.5. Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

8.6. Funding

This research was carried out independently with personal funding and without the financial support of any governmental or private institution or organization.

8.7. Using Artificial Intelligent chatbots

No AI chatbot has been used in this study.

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