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Multifunctional applications of algae in environmental sustainability, food, agriculture, and biotechnology: current advances and future perspectives

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Abstract

Algae represent a diverse and versatile group of photosynthetic organisms with considerable potential for addressing environmental, agricultural, nutritional, and industrial challenges. This review provides an overview of recent advances in algal biotechnology, with particular emphasis on the multifunctional applications of microalgae, macroalgae, and cyanobacteria in environmental sustainability, food and nutrition, agriculture, and health. In environmental applications, algae can serve as bioindicators of pollution and contribute to the removal of heavy metals, nutrients, and organic contaminants from wastewater and other contaminated environments. Their roles in nitrogen fixation, soil improvement, carbon sequestration, and the development of sustainable agricultural practices are also discussed. From a nutritional perspective, algae provide proteins, essential amino acids, polyunsaturated fatty acids, vitamins, minerals, dietary fiber, polysaccharides, and other bioactive compounds, supporting their incorporation into functional foods, fermented products, meat and dairy formulations, and cereal-based foods. Algal-derived compounds, including carotenoids, phycobiliproteins, polyphenols, polysaccharides, sterols, and bioactive peptides, have demonstrated antioxidant, anti-inflammatory, antimicrobial, antidiabetic, and potential anticancer activities, although further clinical evidence is required to establish their therapeutic efficacy. The review also considers the potential of algae as sustainable sources of protein, biofuels, bioplastics, and other value-added bioproducts. Despite these advantages, challenges related to cultivation costs, harvesting, biomass processing, environmental variability, food safety, scalability, regulatory requirements, and economic feasibility continue to limit widespread commercialization. Future advances in strain improvement, integrated cultivation systems, algal–microbial interactions, resource recovery, and algal biorefineries may help overcome these limitations. Overall, algae represent promising biological platforms for developing circular and sustainable solutions across food production, agriculture, environmental management, and biotechnology.

Keywords: Algae; Biotechnology; Bioremediation; Nutrition; Sustainability

1 Introduction

Algae comprise a highly diverse group of organisms, ranging from unicellular microalgae such as *Chlorella* to larger groups, including seaweeds or macroalgae such as *Ulva* and *Laminaria* (1). Algae lack true stems, roots, and leaves, as well as specialized vascular systems for water transport within their bodies; consequently, they rely on direct absorption of water from their surrounding aquatic environments. Algae inhabit a wide range of environments, including lakes, rivers, oceans, deserts, and even extremely cold or highly acidic habitats (2). Their ability to thrive under diverse environmental conditions and utilize a broad range of resources makes them important contributors to the maintenance of planetary health. Algae are estimated to produce approximately half of the oxygen present on Earth and to absorb nearly one-quarter of atmospheric carbon dioxide (3).

Humans have consumed algae and cyanobacteria for centuries. For example, *Spirulina* and *Aphanizomenon* were consumed by the Aztecs and remain part of the diets of certain populations today because of their nutritional value and associated health benefits. More recently, however, researchers have increasingly explored the use of algae-derived enzymes and other algal products in major applications, including food and energy production, as well as environmental remediation. This field is developing rapidly. Currently, about 420 companies specializing in algal cultivation operate in Europe, with approximately half focusing on the cultivation of *Chlorella* and *Spirulina* while another substantial proportion—approximately one-third—cultivate larger seaweed species (4).

In the environmental sector, algae such as *Chlorella vulgaris* are recognized for their potential in wastewater treatment, removing up to 95% of nitrogen and 88% of phosphorus from water. They can also reduce concentrations of heavy metals, including lead, cadmium, and mercury, as well as persistent chemicals such as dichlorodiphenyltrichloroethane (DDT), a synthetic insecticide. In addition, algae can be used for the production of biofuels, including biodiesel, biogas, and bioethanol. Under suitable conditions, algal biomass can yield approximately 58,700 L of biodiesel per hectare per year, exceeding the yields of many terrestrial crops (5).

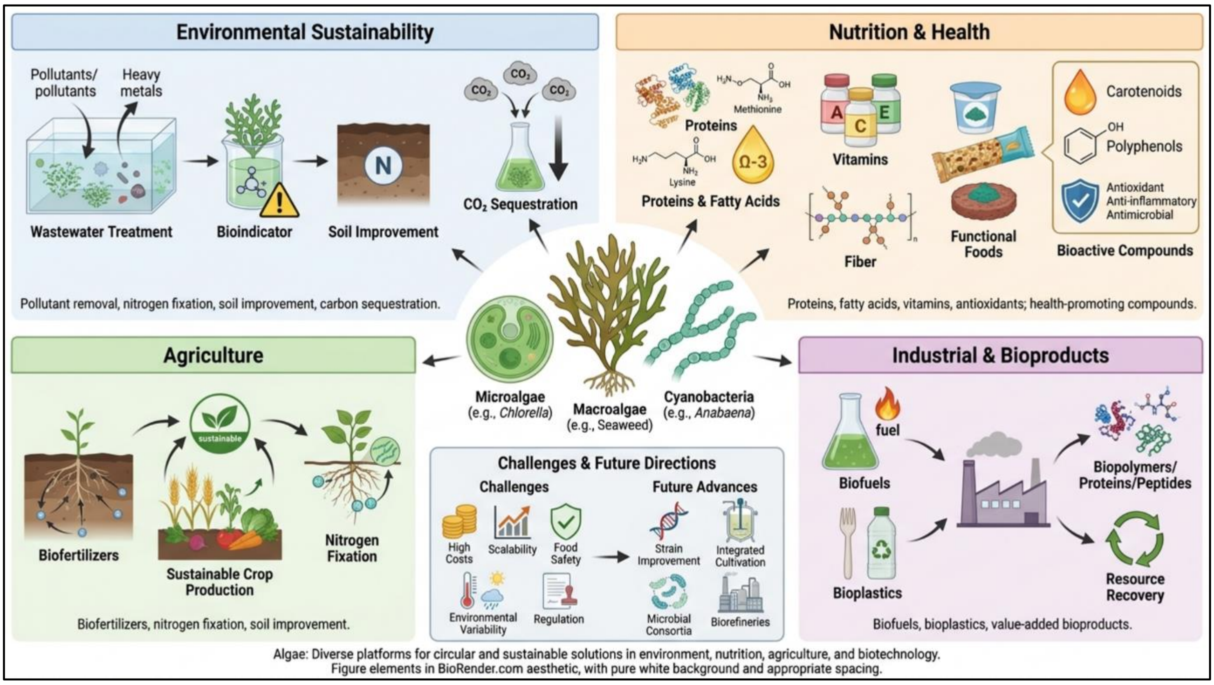

Figure 1: Overview of the current and emerging biotechnological applications of algae. The figure was created exclusively using FigureLabs and BioRender based on the scientific content and conceptual framework developed by the author.

From a nutritional perspective, algae are valuable sources of proteins, healthy lipids, iron, iodine, and various antioxidants. These properties have contributed to their increasing use in the food and dietary supplement industries. The global algal food market is projected to exceed €1.1 billion, with an annual growth rate of up to 6.3%, driven by increasing demand for plant-based and sustainable foods (6). Despite this progress, significant research gaps remain. Comparative studies evaluating different algal species under standardized conditions are still limited, while the development of integrated algal cultivation systems for food production and wastewater treatment remains at an early stage (7).

This review discusses recent advances in algal biotechnology and examines the role of algae in environmental applications, including carbon sequestration, water purification, and pollution remediation. It also highlights algae as a rich source of proteins, healthy lipids, vitamins, and bioactive compounds with anti-inflammatory, antioxidant, anticancer, and antiviral properties, making them promising candidates for disease prevention and as complementary therapeutic agents. Figure 1 illustrates the broad applications and emerging prospects of algae across various biotechnological fields.

2 Algae in Environmental Applications

Algae are natural agents that contribute to addressing a wide range of environmental challenges, including water purification and the maintenance of clean air. They can also serve as bioindicators for detecting air pollution, removing harmful particulate matter and gases, generating energy from sunlight, and maintaining soil health. This section explains how algae contribute to maintaining a cleaner and more sustainable planet through various examples.

2.1 Bioindicators and Environmental Monitoring

Algae, including microalgae and diatoms, play an important role in monitoring pollution levels in lakes and rivers. They respond rapidly to environmental changes, including variations in nutrient availability, metal concentrations, water acidity, and temperature. Because algae form the base of aquatic food networks and respond rapidly to changes in environmental conditions, shifts in their abundance and community composition can provide early indications of changes in water quality and ecosystem health (8). Algae are currently widely used in many countries as indicators for monitoring water quality (9). Recent technological advances, including sensor-based monitoring and algal DNA analysis, have further improved the speed and accuracy of pollution detection, enhancing the potential of algae as effective bioindicators for monitoring and assessing water quality in riverine and marine environments (10).

In particular, diatoms can contribute to water-quality improvement and provide valuable information on environmental conditions. For example, *Gyrosigma* has been identified as a promising candidate for phycoremediation and wastewater treatment, although further experimental validation is required. In contrast, species within the genera *Navicula* and *Nitzschia* are widely reported to tolerate nutrient-enriched and polluted conditions, making their occurrence and abundance useful indicators of trophic status and water quality (11,12). Cyanobacteria, such as *Oscillatoria* and *Anabaena*, can proliferate extensively in phosphorus-rich polluted waters, leading to the phenomenon known as cyanobacterial blooms.

2.2 Bioremediation of Inorganic Pollutants

Algae play an effective role in the treatment of water contaminated with heavy metals such as lead, cadmium, and zinc. They can remove these metals through adsorption onto their cell surfaces or by transporting and accumulating them within their cells. Certain species, such as *Chlamydomonas* and *Chlorella*, can also transform some metals into forms that are less harmful to the environment. In areas where abandoned mining activities contribute to increased water acidity and elevated metal concentrations, algae can help reduce acidity and remove toxic metals from contaminated water. These natural algal processes represent an effective and low-cost approach for treating industrial wastewater. Following treatment, the algal biomass can be harvested, allowing the absorbed metals to be safely recovered or the biomass to be reused, thereby contributing to environmental protection and reducing future waste generation (13).

2.3 Bioremediation of Organic Pollutants

The role of algae extends beyond the removal of heavy metals to the remediation of water and soil contaminated with harmful organic chemicals, including pesticides, pharmaceutical residues, and hormones derived from industrial wastes. Algae can transform these compounds into simpler substances through a range of biochemical reactions, making them easier for natural environmental processes to degrade or assimilate. Certain algal species, such as *Scenedesmus* and *Chlorella*, can utilize some of these pollutants as alternative nutrient sources under nutrient-limited conditions (14).

The use of multiple algal and cyanobacterial species and the development of enhanced algal systems are being investigated to enhance removal efficiency for a broader range of pollutants. For example, *Spirulina* is being investigated for its potential in bioremediation, while mixed algal cultures are being evaluated for the degradation of hormones such as estrone and estradiol. These algae can contribute to water purification by adsorbing harmful compounds, chemically transforming them, or facilitating their degradation through sunlight-driven processes (15). The effectiveness of these processes depends on environmental factors such as light availability, temperature, and pH. When cultivated in controlled systems, such as specialized tanks or constructed wetlands, and maintained under suitable conditions, algae can remove pollutants from water more efficiently. The integration of algae with beneficial bacteria and the application of advanced remediation technologies are also being investigated to enhance the removal of a broader range of contaminants (16). This environmentally friendly approach generally requires less energy and produces fewer significant secondary environmental impacts. An additional advantage is that, when the algal biomass is safe for reuse, it can be converted into valuable products such as fertilizers, animal feed, or even biofuels. In this way, algal bioremediation has the potential to transform pollutants into useful resources while supporting more sustainable waste-management practices (16).

2.4 The Role of Algae in Nitrogen Fixation and Agriculture

Nitrogen-fixing microorganisms contribute to soil health by adding essential nutrients such as nitrogen, thereby promoting plant growth and increasing crop productivity. Certain algae and cyanobacteria, can capture atmospheric nitrogen and convert it into forms that can be utilized by plants. This process, known as biological nitrogen fixation, is facilitated by heterocysts, which provide a suitable environment for nitrogen fixation and the conversion of atmospheric nitrogen into plant-available nitrogen compounds. Genera such as *Anabaena*, *Nostoc*, and *Oscillatoria* are commonly used in rice and wheat cultivation to improve soil fertility and reduce the need for chemical fertilizers (10).

These species can also release beneficial compounds, including phytohormones and vitamins, which promote plant growth. When used as green manure or incorporated into biofertilizer production, they can improve soil quality, enhance water retention, and support the growth and activity of beneficial microorganisms associated with plants. The use of algae in agriculture can therefore reduce reliance on agrochemicals while contributing to carbon sequestration in agricultural soils and potentially reducing greenhouse gas emissions. The potential of algae to assimilate carbon and tolerate adverse environmental conditions has also been investigated, highlighting their potential applications in sustainable agricultural systems(17).

2.5 Other Environmental Applications of Algae

Beyond their agricultural applications, algae are increasingly being investigated as renewable feedstocks for biofuels, bioplastics, and other sustainable materials, including materials with potential applications in construction. In addition, algae-based air-purification systems are being developed to capture CO_2 and generate oxygen, with potential applications in improving indoor air quality (18–20). Algae can also help protect soil from erosion in arid and coastal regions by forming dense layers that stabilize the soil and prevent its displacement. In marine ecosystems, macroalgae provide shelter and habitat for marine organisms while also contributing to the absorption and sequestration of atmospheric carbon (21).

Collectively, these applications demonstrate the diverse and important roles of algae in environmental protection and their potential to provide sustainable solutions to a range of environmental challenges.

3 Food and Nutrition using Algae

3.1 Algae in Food

Algae, including both macroalgae (seaweeds) and microalgae, have long been valued for their nutritional properties. In Asian countries, particularly in Japan and Korea, seaweeds are a regular component of the daily diet, whereas their use in Western countries is relatively recent. The growing demand for plant-based, nutrient-rich, and sustainable foods has driven the development of food products based on algae. Owing to their diversity, algae can be consumed directly or incorporated as functional ingredients into a wide range of food products. Their potential use in future food systems is also being actively investigated as a means of supporting sustainability goals and addressing nutritional deficiencies in both developing and developed countries (22).

3.2 Nutritional Composition of Algae

Algae and cyanobacteria are rich in nutrients and provide concentrated sources of high-quality proteins, essential amino acids, polyunsaturated fatty acids, vitamins and minerals. *Chlorella* and *Spirulina* are among the most widely used as nutritional supplements due to their high protein content and abundance of antioxidant compounds. Seaweeds, including brown, red, and green algae, are also good sources of iodine, calcium, magnesium, and bioactive compounds such as polyphenols and carotenoids. These nutrients contribute to the maintenance of cardiovascular, gastrointestinal, and immune health. In addition, algae provide complex polysaccharides that may support gut health and influence various metabolic functions (23).

3.3 Algal Polysaccharides and Gelling Compounds

Marine algae are major industrial sources of three important polysaccharides: alginates, agar, and carrageenan. These compounds are widely used in the food industry because of their ability to modify texture, stabilize formulations, and improve the quality and shelf life of various food products.

Algae-derived polysaccharides, particularly alginate, agar, and carrageenan, are important functional compounds with diverse technological and industrial applications. Alginate is obtained mainly from brown seaweeds such as *Laminaria* and *Ascophyllum* and is valued for its excellent gelling, thickening, stabilizing, and film-forming properties. These characteristics make alginate useful in food formulations as well as pharmaceutical and biomedical applications, including hydrogel formation, drug delivery, and wound-dressing materials. Agar is primarily extracted from red seaweeds such as *Gelidium* and *Gracilaria* and is characterized by its strong, thermoreversible gel-forming ability, making it widely used as a gelling and stabilizing agent in food products and as a solidifying component of microbiological culture media. Carrageenan, also derived mainly from red seaweeds such as *Eucheuma* and *Chondrus*, possesses variable gelling, thickening, stabilizing, and water-binding properties depending on its chemical structure, and is therefore widely used in food, pharmaceutical, and other industrial formulations. Beyond these technological applications, these seaweed-derived polysaccharides have attracted considerable scientific interest because of their diverse biological activities and potential biomedical and health-related applications, including antioxidant, antimicrobial, antiviral, anticoagulant, and other functional properties. Their physicochemical characteristics, biodegradability, and biological activities further support their potential use in the development of sustainable and value-added products (24).

3.4 Algae-Based Functional Foods and Nutritional Applications

Algae and cyanobacteria are increasingly used in the development of functional foods, which are food products that provide health benefits beyond their basic nutritional value. For example, brown algae are incorporated into some bread and cereal products to help modulate the change in blood glucose concentration following consumption. Extracts of *Spirulina* and *Dunaliella* are also added to beverages and snack products because of their high content of antioxidant compounds. In addition, algal ingredients can improve both the texture and functional properties of dairy products, including yogurt and processed cheese. This versatility makes algae valuable and adaptable ingredients for meeting the evolving demands of the health-oriented food market (25).

3.5 Applications in Meat, Fish, and Dairy Products

Algae are increasingly being investigated as functional ingredients for improving the quality, nutritional value, and technological properties of meat and seafood products. Their incorporation can enhance important characteristics such as water-holding capacity, emulsification, texture, color, and oxidative stability, while providing proteins, dietary fiber, minerals, pigments, polyunsaturated fatty acids, and other bioactive compounds. Seaweeds such as *Pyropia* sp. or *Porphyra* sp. and *Undaria pinnatifida*, for example, can be incorporated into meat formulations to improve nutritional composition and functional properties while contributing antioxidant compounds that may help limit lipid oxidation (1). Similarly, the incorporation of algal biomass into fish patties and other seafood products has been investigated as a means of increasing their nutritional value without substantially compromising sensory characteristics such as flavor, aroma, texture, and overall acceptability. Algal extracts and bioactive compounds have also shown potential for protecting fish oils and other lipid-rich seafood products against oxidation, thereby improving product stability and potentially extending shelf life. These applications demonstrate the potential of algae to serve not only as nutritional ingredients but also as multifunctional components capable of improving the physicochemical stability and quality of animal-derived foods (4,22,26).

Algae-derived compounds also have important applications in dairy and other formulated foods, particularly because of their thickening, gelling, emulsifying, and stabilizing properties. Carrageenan obtained from red seaweeds is widely used as a functional hydrocolloid in dairy formulations, where it can interact with milk proteins and help maintain a uniform structure, reduce phase separation, and provide desirable texture in products such as chocolate milk, ice cream, and other dairy-based formulations (6,25,27). Other algal polysaccharides and extracts may similarly contribute to water retention, viscosity, emulsion stability, and product consistency. In addition to their technological functions, algae-derived ingredients can contribute valuable nutrients and bioactive compounds, creating opportunities to improve the nutritional profile of processed foods while reducing dependence on some conventional synthetic additives. Consequently, the incorporation of algae into meat, seafood, and dairy products represents a promising approach for developing nutritionally enhanced, functionally improved, and more sustainable food products, particularly in response to increasing consumer interest in natural ingredients and environmentally sustainable food production (28).

3.6 Applications in Cereals and Bakery Products

Algae are increasingly incorporated into bread, pasta, and snack products to enhance their nutritional value, particularly by increasing dietary fiber and mineral content. Studies have shown that incorporating *Ulva lactuca* or *Laminaria* into bread can increase its mineral content. These effects highlight the potential of algal ingredients to improve the nutritional profile of commonly consumed cereal-based foods (6,7,27).

Similarly, pasta enriched with algae such as *Sargassum* or *Monostroma* can exhibit improved textural properties and enhanced bioactive potential. Such products may therefore represent promising alternatives for health-conscious consumers and those seeking dietary strategies that support the prevention of chronic diseases. Algal ingredients are also being investigated for their potential application in gluten-free food systems, further expanding their role in the development of nutritionally enhanced and functional cereal-based products (29).

3.7 Fermented Algal Foods

The combination of algae with fermented food products can provide additional probiotic and functional benefits. Lactic acid bacteria commonly used in dairy fermentation can interact effectively with algal ingredients, contributing to the development of novel foods with enhanced health-promoting properties. Algal biomass can provide a suitable substrate for the growth of beneficial bacteria, which may improve product texture and shelf life while potentially contributing to cholesterol reduction and improved gut health (7,25).

Algal extracts and biomass from seaweeds and microalgae have already been incorporated into fermented products such as yogurt, kefir, and cheese. Fermentation can also reduce certain antinutritional compounds, thereby improving the bioavailability of essential nutrients and enhancing the overall nutritional quality of the resulting products (29).

3.8 Health Benefits and Therapeutic Roles

Algae have promising potential for disease prevention and health promotion because they contain a wide range of bioactive compounds with antioxidant, anti-inflammatory, antimicrobial, and antidiabetic properties. Compounds such as fucoxanthin from brown algae and phycocyanin from *Spirulina* are currently being investigated for their potential roles in reducing metabolic and oxidative stress. Algal consumption has also been associated with potential benefits for cardiovascular health, weight management, and immune function (7).

In addition, polysaccharides such as laminarin and ulvan have demonstrated prebiotic effects by promoting the growth and activity of beneficial intestinal bacteria. Algae also contain sterols and bioactive peptides that may exert antihypertensive and cholesterol-lowering effects. Furthermore, in vitro and animal studies have provided evidence of potential anticancer properties of various algal compounds. However, further well-designed human clinical trials are required to establish their efficacy, safety, and therapeutic potential in disease prevention and treatment (28).

3.9 Algae as a Sustainable Protein Source

Microalgae such as *Chlorella* spp. are valuable sources of high-quality protein and can provide all essential amino acids. Compared with conventional animal protein production, algal cultivation generally requires less land and water and can generate lower greenhouse gas emissions. Algae can also be cultivated on non-arable land and, under suitable conditions, in saline water or wastewater, thereby reducing competition with conventional agricultural crops (30). Because of their rapid growth rates and high protein productivity per unit of land area, microalgae represent a promising option for supporting future food security and the development of more sustainable protein sources (26). Current research is focused on improving the sensory characteristics, digestibility, and processing methods of algal proteins to facilitate their broader incorporation into conventional diets and food products.

4 Challenges and Limitations of Algal Biotechnology

Despite the considerable potential of algae in environmental management, agriculture, food production, and biotechnology, several challenges still limit their large-scale application. One of the main obstacles is the cost of algal cultivation and biomass processing. Large-scale production requires appropriate cultivation systems, reliable sources of light, nutrients, carbon dioxide, and water, as well as efficient harvesting and downstream processing methods. In particular, harvesting and dewatering can account for a substantial proportion of the total production cost because algal cells are generally small and suspended at relatively low concentrations in the culture medium. Developing low-energy and cost-effective harvesting technologies is therefore essential for improving the economic feasibility of algal production.

Another important challenge is the stability and productivity of algal cultures. Factors such as temperature, light intensity, pH, nutrient availability, salinity, and contamination by unwanted microorganisms can significantly affect biomass productivity and biochemical composition. Although controlled cultivation systems can provide more stable conditions, they require greater infrastructure and operational costs. Outdoor cultivation systems are generally less expensive to operate but are more susceptible to seasonal variations and contamination, which can reduce productivity and affect the consistency of the final product.

The use of algae for food and nutritional applications also presents several challenges. Although algae can provide proteins, minerals, vitamins, lipids, and bioactive compounds, their nutritional composition can vary considerably according to species, cultivation conditions, harvesting stage, and processing methods. Some algal products may also have strong colors, marine or earthy flavors, or textural characteristics that limit consumer acceptance. In addition, certain species may accumulate heavy metals, iodine, or other undesirable compounds when cultivated in contaminated environments. Therefore, appropriate monitoring, processing, quality control, and regulatory standards are necessary to ensure the safety and consistency of algal-derived food products.

For environmental applications, laboratory-scale results do not always translate directly into efficient large-scale systems. Factors such as pollutant concentration, water chemistry, biomass concentration, light availability, and interactions with other microorganisms can influence treatment performance. Furthermore, the algal biomass generated during wastewater treatment may contain accumulated pollutants and therefore cannot always be safely reused as food, feed, or fertilizer. Appropriate biomass management and, where possible, recovery of valuable compounds are consequently important components of sustainable algal treatment systems.

Economic feasibility and environmental sustainability also require further evaluation. Although algae can potentially reduce land use, recycle nutrients, capture carbon, and generate multiple valuable products, cultivation and processing may require significant energy and resources. The overall environmental benefits therefore depend on the cultivation system, energy source, water requirements, nutrient inputs, and efficiency of downstream processing. Life-cycle assessment and techno-economic analysis are needed to determine whether specific algal technologies provide genuine environmental and economic advantages over conventional alternatives.

Finally, regulatory frameworks, consumer acceptance, and commercialization remain important barriers. The development of algal products for food, feed, pharmaceuticals, and environmental applications requires compliance with appropriate safety and quality standards. Greater consistency in cultivation, processing, and product characterization will be necessary to facilitate commercialization. Addressing these challenges through improved cultivation technologies, strain selection, process optimization, integrated biorefineries, and better resource recovery will be essential for translating the promising potential of algae into economically viable and environmentally sustainable applications.

5 Future Perspectives

The future development of algal biotechnology is closely linked to advances in strain selection and improvement, cultivation technologies, resource recovery, bioprocessing, and system integration. Continued research is expected to identify algal strains with higher biomass productivity, improved nutrient uptake, greater tolerance to environmental stresses, and enhanced production of specific valuable compounds. Advances in genetic, metabolic, and synthetic biology may further enable the development of strains with tailored characteristics for particular applications, including soil improvement, wastewater treatment, carbon capture, food production, biofuels, and the synthesis of high-value bioactive compounds. In agriculture, algal strains with enhanced nitrogen-use efficiency and the ability to produce compounds that promote plant growth or contribute to pest management could provide alternatives to some conventional agricultural inputs. Algae-based biofertilizers may be particularly valuable in areas with poor soil fertility or limited access to commercial fertilizers by improving nutrient availability and supporting soil quality. Their integration into sustainable agricultural systems may also contribute to carbon retention in soils and reductions in greenhouse-gas emissions (7).

A particularly promising direction is the development of integrated algal cultivation systems that simultaneously address environmental problems and generate valuable biomass. Algae can be cultivated using nutrient-rich wastewater, allowing nitrogen and phosphorus to be recovered while producing biomass that may subsequently be converted into biofertilizers, biofuels, animal feed, food ingredients, or other bioproducts, provided that appropriate safety requirements are met. Such systems could reduce the need for freshwater and external nutrients while lowering production costs and supporting nutrient recycling within a circular bioeconomy. Integration with existing wastewater treatment plants, agricultural operations, and industrial processes may further improve resource efficiency by allowing algae to utilize available nutrients, carbon dioxide, and waste streams rather than requiring completely independent cultivation infrastructure. Algae–bacteria systems represent another important opportunity because interactions between algae and beneficial microorganisms can enhance nutrient removal, biomass productivity, and the degradation of certain complex organic pollutants.

Algae also have considerable potential to contribute to climate-change mitigation and environmental management. Their ability to assimilate carbon dioxide through photosynthesis provides opportunities for integrating algal cultivation with concentrated carbon sources, while their application in wastewater treatment, air purification, and other remediation processes could provide multiple environmental benefits within a single system. However, the overall environmental performance of these approaches depends on the energy, water, nutrients, and infrastructure required for cultivation, harvesting, and downstream processing. Future systems should therefore emphasize low-energy cultivation, efficient carbon and nutrient utilization, water recycling, renewable energy, and recovery of valuable products. Algae may also contribute to the development of green infrastructure and sustainable approaches to soil restoration, erosion control, waste treatment, and pollution remediation, particularly where environmental treatment can be combined with biomass production.

The growing concern over plastic pollution and dependence on fossil-based materials is expected to further stimulate research into algae-derived biomaterials. Algal polysaccharides, proteins, lipids, and other biomass components can serve as feedstocks for biodegradable films, packaging materials, biopolymers, and other value-added products. Continued advances in extraction, fractionation, and material-processing technologies may improve the mechanical properties, stability, biodegradability, and functionality of these materials, increasing their suitability for practical applications. At the same time, the development of algal biorefineries offers an important strategy for improving economic feasibility. Rather than relying on a single product, integrated biorefineries can fractionate algal biomass into multiple products, including proteins, pigments, lipids, polysaccharides, bioactive compounds, fertilizers, and fuels. Maximizing the value obtained from each unit of biomass while minimizing waste could substantially improve the economic performance and sustainability of large-scale algal production.

Future research should also expand the role of algae in sustainable food systems. Improved processing technologies may help overcome current limitations related to undesirable flavors, colors, textures, protein digestibility, and nutrient bioavailability, facilitating the incorporation of algal ingredients into familiar food products. Algal proteins, polysaccharides, lipids, pigments, and bioactive compounds could provide alternative sources of nutrients and functional ingredients in response to increasing demand for sustainable food resources. However, wider commercialization will require rigorous attention to food safety, contaminant accumulation, nutritional consistency, allergenicity, consumer acceptance, and regulatory requirements. Similar considerations apply to agricultural and environmental applications, where the safety of biomass produced from wastewater or contaminated environments must be carefully evaluated before its use as food, feed, or fertilizer.

Despite their considerable potential, several challenges must be addressed before algal technologies can achieve widespread commercial and environmental application. These include high cultivation and harvesting costs, energy requirements, contamination, variable productivity, difficulties in biomass processing, seasonal and environmental fluctuations, and the need for reliable large-scale production systems. Economic assessments and life-cycle analyses will therefore be essential for determining whether proposed algal applications provide genuine environmental benefits compared with existing technologies. Future development should focus not simply on increasing algal biomass productivity, but on optimizing the entire production chain—from strain selection and cultivation to harvesting, processing, product recovery, and waste management. Interdisciplinary collaboration among biotechnology, agriculture, environmental engineering, food science, materials science, microbiology, and process economics will be essential for overcoming these barriers.

Overall, the future of algal biotechnology will depend on the successful integration of biological innovation with efficient, economically viable, and environmentally responsible production systems. The combination of improved algal strains, integrated cultivation, microbial associations, wastewater and carbon-resource recovery, and multi-product biorefinery approaches could enable algae to contribute simultaneously to sustainable agriculture, environmental remediation, renewable energy, food production, biomaterials, and resource recovery. With appropriate technological development, safety assessment, economic evaluation, and investment, algae have the potential to become an important component of circular bioeconomy systems and long-term sustainable development.

6 Conclusion

Algae are highly versatile organisms with considerable potential for supporting environmentally sustainable agriculture. They can contribute to soil improvement, reduce reliance on chemical inputs, support clean energy production, and provide sustainable alternatives for the development of environmentally friendly materials. Their ability to fix nitrogen, promote plant growth, and support beneficial soil microorganisms enables them to play an important role in organic and low-input agricultural systems. In addition, their capacity to sequester carbon and contribute to pollution remediation makes them valuable tools for addressing climate change and a range of environmental challenges.

Through continued research, technological development, and innovation, algae have the potential to contribute to healthier food systems, cleaner environments, and long-term sustainability. Further advances in algal biotechnology will be essential for translating these capabilities into scalable and economically viable solutions across agriculture, food production, environmental management, and other emerging applications.

Statements on Compliance with Ethical Standards

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