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Algae: Green lungs and carbon warriors of Earth

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Abstract: *Climate change, biodiversity loss, and increasing atmospheric carbon dioxide (CO_2) concentrations are among the most pressing environmental challenges. Addressing these interconnected issues requires innovative and nature-based solutions, and algae have emerged as one of the most promising biological resources. Ranging from microscopic phytoplankton and unicellular microalgae to large multicellular seaweeds, algae are fundamental to the health of aquatic ecosystems and the stability of the Earth's climate. Through photosynthesis, they contribute nearly half of the global oxygen supply, earning them recognition as the 'green lungs' of the planet. Additionally, their exceptional capacity to capture and store atmospheric CO_2 positions them as natural 'carbon warriors' that help mitigate the impacts of global warming. Marine phytoplankton drive the biological carbon pump, transferring carbon from the atmosphere to deep ocean reservoirs, while cultivated macroalgae and microalgae offer sustainable approaches for carbon sequestration and environmental restoration. In addition, algae have gained considerable attention for their diverse applications in biotechnology. They serve as renewable sources of food, feed, biofuels, pharmaceuticals, nutraceuticals, cosmetics, and biodegradable biomaterials. Algae are also increasingly utilized in wastewater treatment and bioremediation, owing to their ability to remove excess nutrients, heavy metals, and other pollutants from aquatic environments. Recent advances in algal biotechnology, synthetic biology, and bioprocess engineering are further expanding their commercial potential. This article highlights the indispensable ecological services provided by algae, examines their multifaceted applications, and emphasizes their growing role as a sustainable solution for combating climate change, enhancing environmental resilience, and supporting global efforts toward sustainable future.*

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1. Introduction

When people think of the "lungs of the Earth," vast tropical rainforests such as the Amazon are often regarded as the primary source of the planet's oxygen. Although forests are indispensable for maintaining terrestrial biodiversity, regulating regional climates, and storing carbon, the role of aquatic photosynthetic organisms in sustaining life on Earth is frequently overlooked. Among these, algae—an extraordinarily diverse group of photosynthetic organisms ranging from microscopic unicellular microalgae and marine phytoplankton to large multicellular seaweeds—perform ecological functions that are equally, if not more, significant on a global scale. Having evolved more than 2.5 billion years ago, algae were among the earliest organisms capable of oxygenic photosynthesis, fundamentally transforming Earth's atmosphere by increasing oxygen concentrations and paving the way for the evolution of complex life [1].

Algae inhabit an extraordinary range of environments, including oceans, freshwater ecosystems, wetlands, polar ice, hot springs, deserts, and even symbiotic associations with fungi and corals. Their remarkable adaptability allows them to flourish under diverse environmental conditions, making them one of the most widespread and productive groups of organisms on the planet. Marine phytoplankton alone contribute nearly half of the Earth's annual primary production despite accounting for less than 1% of the global photosynthetic biomass, underscoring their exceptional photosynthetic efficiency [2]. Through photosynthesis, algae utilize sunlight to convert atmospheric carbon dioxide (CO_2) and water into organic compounds while releasing oxygen, thereby supporting both aquatic and terrestrial life.

Because of their immense contribution to oxygen generation, algae are increasingly recognized as the "green lungs" of the planet. It is estimated that marine phytoplankton produce approximately 45–50% of the oxygen released into the atmosphere each year, making every second breath taken by humans indirectly dependent on these microscopic organisms [3]. In addition to oxygen production, algae form the foundation of aquatic food webs by serving as primary producers that sustain zooplankton, fish, marine mammals, and countless other organisms. Consequently, the health and productivity of aquatic ecosystems are intrinsically linked to the abundance and diversity of algal communities [4].

Equally important is the role of algae as "carbon warriors" in mitigating climate change. Through rapid photosynthesis, algae efficiently absorb atmospheric CO_2 and convert it into biomass, thereby reducing greenhouse gas concentrations. Marine phytoplankton drive the biological carbon pump, a natural process through which organic carbon is transported from the ocean surface to deeper waters and sediments for long-term storage, significantly influencing the global carbon cycle [5]. Coastal macroalgae, including kelp forests and seaweed beds, also contribute to blue carbon sequestration by capturing carbon and exporting a portion of their biomass to deep marine environments, where carbon can remain stored for decades to centuries [6].

Beyond their ecological significance, algae have emerged as versatile biological resources capable of supporting sustainable development. Advances in algal biotechnology have demonstrated their potential in producing renewable biofuels, high-value pharmaceuticals, nutraceuticals, natural pigments, biodegradable bioplastics, biofertilizers, and animal feed. Furthermore, algae are increasingly employed in wastewater treatment and bioremediation because of their capacity to remove excess nutrients, heavy metals, and organic pollutants while simultaneously generating valuable biomass [7]. Their rapid growth rates, minimal land requirements, and ability to thrive using saline or wastewater further distinguish algae as environmentally sustainable alternatives to conventional agricultural and industrial resources [8].

As the world seeks innovative, nature-based solutions to address climate change, environmental degradation, and resource scarcity, algae have gained unprecedented scientific and industrial attention. Integrating algal systems into carbon capture technologies, circular bioeconomy models, and ecosystem restoration strategies offers a promising pathway toward achieving global sustainability goals [7]. Recognizing algae not merely as aquatic organisms but as indispensable regulators of planetary health is essential for fostering future conservation efforts and advancing green technologies capable of securing a more resilient and sustainable future [6].

1. Algae: The Earth's Hidden Oxygen Factories

Photosynthesis is the fundamental biological process that sustains life on Earth by converting solar energy into chemical energy while releasing oxygen as a by-product. Although terrestrial forests are widely recognized for their contribution to oxygen production, aquatic photosynthetic organisms—particularly algae—play an equally critical, and often underestimated, role in maintaining the planet's atmospheric balance. Marine phytoplankton, together with freshwater microalgae and macroalgae, are responsible for nearly half of the global photosynthetic activity and contribute approximately 45–50% of the Earth's annual oxygen production [9]. These microscopic organisms form the foundation of aquatic ecosystems and regulate biogeochemical cycles that are essential for maintaining life on Earth.

Marine phytoplankton comprise diverse groups of microalgae, including diatoms, dinoflagellates, coccolithophores, and cyanobacteria, which collectively dominate primary productivity across the world's oceans. Despite representing only a minute fraction of the Earth's total plant biomass, they account for an estimated 40–50 gigatons of carbon fixation annually, demonstrating one of the highest photosynthetic efficiencies among all living organisms [10]. Through oxygenic photosynthesis, algae absorb atmospheric and dissolved carbon dioxide (CO_2), utilize sunlight as an energy source, and convert inorganic carbon into organic matter while releasing molecular oxygen. This continuous process has maintained atmospheric oxygen concentrations for millions of years and remains indispensable for supporting aerobic life [1].

Unlike terrestrial forests that require years or even decades to establish mature canopies, most microalgae possess exceptionally rapid growth rates, with some species capable of doubling their biomass within 24 hours under favourable environmental conditions [11]. Their rapid cell division enables them to respond quickly to changing environmental conditions and sustain high levels of photosynthetic productivity throughout the year. Because of this extraordinary reproductive capacity, algal communities can generate substantial amounts of oxygen in relatively short periods, making them highly efficient biological converters of solar energy into biomass [9]. Every breath humans take is therefore linked, either directly or indirectly, to the photosynthetic activity of these microscopic organisms inhabiting oceans, lakes, rivers, wetlands, and other aquatic ecosystems [10].

The ecological significance of algae extends well beyond oxygen production. As primary producers, algae constitute the first trophic level of aquatic food webs and support the productivity of both freshwater and marine ecosystems. Phytoplankton serve as the principal food source for zooplankton, which are subsequently consumed by fish, crustaceans, mollusks, and other aquatic organisms. These organisms, in turn, sustain higher trophic levels, including commercially important fish species, seabirds, marine mammals, and humans. It is estimated that nearly 90% of marine fish production depends directly or indirectly on phytoplankton-based food chains, highlighting the indispensable ecological role of algae in maintaining global fisheries and food security [12].

In addition to supporting biodiversity, algal photosynthesis plays a central role in regulating global nutrient and biogeochemical cycles. During photosynthesis, algae assimilate carbon, nitrogen, phosphorus, silicon, and trace elements into their biomass, facilitating nutrient recycling within aquatic ecosystems. Following their life cycle, algal biomass becomes available to decomposers or is transferred through food webs, thereby maintaining ecosystem productivity and stability. Furthermore, healthy phytoplankton populations influence the exchange of gases between the ocean and atmosphere, regulate ocean chemistry, and contribute to climate regulation by coupling oxygen production with carbon sequestration [13].

However, the productivity of these hidden oxygen factories is increasingly threatened by anthropogenic pressures, including climate change, ocean warming, acidification, pollution, eutrophication, and habitat degradation. Rising sea surface temperatures can alter phytoplankton community composition and reduce primary productivity in several oceanic regions, while excessive nutrient loading from agricultural runoff promotes harmful algal blooms that disrupt ecosystem functioning and reduce water quality [14]. Protecting aquatic ecosystems and maintaining healthy algal populations have therefore become global conservation priorities, not only for preserving biodiversity but also for safeguarding the Earth's oxygen balance and climate stability [15].

As scientific understanding of algal ecology continues to expand, these seemingly inconspicuous organisms are increasingly recognized as indispensable components of the Earth's life-support system. Their extraordinary ability to produce oxygen, sustain aquatic food webs, regulate nutrient cycling, and maintain ecological resilience underscores why algae deserve recognition as the Earth's hidden oxygen factories. Conserving natural algal habitats while advancing sustainable algal cultivation technologies will be critical for ensuring environmental health, food security, and climate resilience in the decades to come [7].

2. Algae: Nature's Carbon Warriors in Climate Change Mitigation

One of the most remarkable ecological functions of algae is their exceptional ability to capture and utilize atmospheric carbon dioxide (CO_2), making them one of nature's most efficient biological tools for climate change mitigation. Through oxygenic photosynthesis, algae absorb CO_2 from the atmosphere or surrounding water and convert it into organic compounds such as carbohydrates, proteins, lipids, pigments, and nucleic acids using sunlight as the primary energy source. This process not only sustains algal growth but also removes significant quantities of greenhouse gases from the environment, thereby contributing to the regulation of the Earth's carbon balance. Compared with many terrestrial plants, numerous microalgal species exhibit substantially higher photosynthetic efficiencies and faster biomass accumulation rates, enabling them to fix carbon at remarkably rapid rates under favourable environmental conditions [16]. These characteristics have positioned algae as promising biological platforms for natural carbon sequestration and climate-smart biotechnology.

Marine phytoplankton are particularly important because they form the foundation of the global carbon cycle. Collectively, they account for nearly half of global primary production and assimilate approximately 40–50 gigatons of carbon annually, thereby regulating the exchange of carbon dioxide between the atmosphere and the oceans [17]. During photosynthesis, dissolved inorganic carbon is transformed into organic biomass that enters marine food webs or remains suspended in the water column. This continuous uptake of atmospheric CO_2 helps maintain equilibrium between atmospheric and oceanic carbon reservoirs and reduces the accumulation of greenhouse gases responsible for global warming [10].

A significant proportion of the carbon fixed by marine algae is transported to the deep ocean through a naturally occurring process known as the biological carbon pump. After phytoplankton complete their life cycle, many cells die or aggregate into larger particles that gradually sink into deeper ocean layers. Some of this organic matter is consumed and recycled by marine organisms, whereas a fraction escapes decomposition and becomes buried in deep-sea sediments, effectively locking away carbon for centuries to millennia [18]. This long-term sequestration represents one of the Earth's most important natural climate-regulating mechanisms, preventing large quantities of carbon from returning to the atmosphere. Recent studies estimate that the biological carbon pump transfers nearly 10–12 gigatons of carbon each year from surface waters to the deep ocean, thereby playing a crucial role in stabilizing atmospheric CO_2 concentrations and moderating global climate [19].

In addition to microscopic phytoplankton, macroalgae (seaweeds) have emerged as important contributors to carbon sequestration through blue carbon ecosystems. Extensive kelp forests and seaweed beds rapidly absorb carbon during growth, and a portion of their biomass is transported offshore and deposited in deep marine sediments. Although seaweeds do not store carbon in soils like mangroves or seagrasses, increasing evidence indicates that they contribute substantially to long-term carbon storage in the ocean and provide valuable ecosystem services, including coastal protection, biodiversity enhancement, and nutrient cycling [20]. Consequently, seaweed cultivation is increasingly being recognized as a nature-based climate solution capable of complementing conventional carbon reduction strategies.

The remarkable carbon-fixing ability of algae has also stimulated the development of algal carbon capture and utilization (CCU) technologies. Researchers are cultivating microalgae in photobioreactors and open raceway ponds supplied with industrial flue gases from thermal power plants, cement factories, steel industries, and other carbon-intensive sectors. Since flue gases typically contain 5–15% CO_2 , they provide an inexpensive carbon source for algal growth while simultaneously reducing industrial emissions [21]. Rather than allowing carbon dioxide to escape into the atmosphere, these systems biologically convert it into valuable biomass that can be processed into biofuels, animal feed, fertilizers, pharmaceuticals, nutraceuticals, pigments, and biodegradable bioplastics. This integrated approach not only lowers greenhouse gas emissions but also supports the development of a circular bioeconomy by transforming industrial waste into commercially valuable products [22].

Recent advances in biotechnology, metabolic engineering, and artificial intelligence have further enhanced the potential of algae for carbon management. Genetic improvement of microalgal strains has increased photosynthetic efficiency, carbon fixation rates, and lipid productivity, while AI-assisted cultivation systems enable real-time optimization of light intensity, nutrient availability, temperature, and CO_2 supply for maximum biomass production [23]. Such innovations are expected to improve the economic feasibility of large-scale algal carbon capture systems and accelerate their commercialization in the coming decades.

Despite these promising developments, several challenges remain before algal carbon sequestration can be widely implemented. Large-scale cultivation requires significant investments in infrastructure, efficient harvesting technologies, water management, and downstream biomass processing. Maintaining stable cultures under varying environmental conditions and minimizing energy consumption during biomass recovery are additional obstacles that researchers continue to address. Nevertheless, ongoing advances in photobioreactor engineering, renewable energy integration, and biorefinery technologies are steadily improving the sustainability and cost-effectiveness of algal cultivation systems [22].

As global efforts intensify to achieve net-zero carbon emissions, algae represent one of the most promising nature-based and technologically adaptable solutions for climate change mitigation. Their unparalleled capacity to capture atmospheric CO_2 , support the biological carbon pump, generate renewable biomass, and integrate with industrial carbon capture technologies underscores their role as true "carbon warriors" of the Earth. Harnessing the full potential of algae will not only contribute to reducing greenhouse gas emissions but also promote sustainable industrial development, environmental restoration, and a resilient low-carbon future.

3. Climate Change and Environmental Restoration: Algae as Nature-based solution

The accelerating impacts of climate change, including rising global temperatures, ocean acidification, extreme weather events, biodiversity loss, and deteriorating water quality, have intensified the search for sustainable and nature-based solutions capable of restoring environmental balance. Among the diverse biological resources being explored, algae have emerged as one of the most promising candidates because of their unique ability to simultaneously address multiple environmental challenges (Figure 1). Beyond their well-established role in carbon sequestration, algae contribute significantly to ecosystem restoration, pollution control, nutrient recycling, habitat enhancement, and climate resilience. Their rapid growth, high photosynthetic efficiency, and adaptability to diverse environmental conditions make them indispensable allies in achieving global sustainability and climate goals [24].

One of the most valuable environmental services provided by algae is wastewater treatment and nutrient recovery. Rapid urbanization, industrialization, and intensive agricultural practices have resulted in excessive discharge of nitrogen and phosphorus into freshwater and coastal ecosystems. Elevated nutrient concentrations promote eutrophication, a process characterized by excessive algal blooms, oxygen depletion, fish mortality, and degradation of aquatic biodiversity. Controlled cultivation of beneficial microalgae provides an effective biological solution by assimilating these excess nutrients into their biomass during growth. Species such as *Chlorella*, *Scenedesmus*, and *Spirulina* efficiently remove ammonium, nitrate, and phosphate from municipal, agricultural, and industrial wastewater while producing valuable biomass that can subsequently be utilized for biofertilizers, bioenergy, or animal feed [25]. This integrated approach supports the principles of the circular bioeconomy by converting waste streams into economically valuable products while minimizing environmental pollution.

In addition to nutrient removal, algae possess remarkable bioremediation capabilities through their ability to absorb, accumulate, and detoxify a wide range of environmental pollutants. Many microalgal species can bind and sequester toxic heavy metals such as cadmium, lead, mercury, chromium, arsenic, and nickel through biosorption and bioaccumulation mechanisms. Their cell walls contain functional groups—including hydroxyl, carboxyl, sulfate, and phosphate groupsthat effectively bind metal ions and reduce their bioavailability in contaminated waters [26]. Furthermore, algae have demonstrated the capacity to degrade or remove pesticides, pharmaceutical residues, dyes, hydrocarbons, and emerging contaminants such as microplastics and endocrine-disrupting chemicals. These properties have positioned algal biotechnology as an environmentally friendly alternative to conventional physicochemical wastewater treatment methods, which are often energy-intensive and expensive [27].

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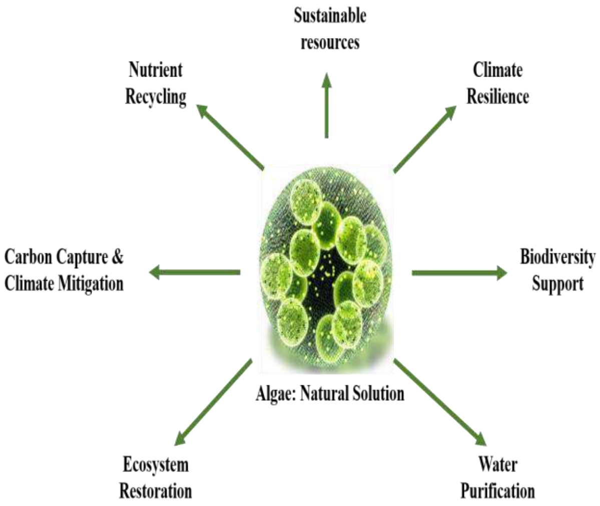

Figure 1: Algae working as nature-based solution for restoring environment.

Another emerging contribution of algae to environmental restoration lies in the development of blue carbon ecosystems. Traditionally, mangroves, seagrasses, and salt marshes have been recognized as the primary blue carbon habitats because of their ability to capture and store atmospheric carbon within coastal sediments. However, recent research has expanded this concept to include macroalgae (seaweeds), particularly extensive kelp forests and cultivated seaweed farms. Seaweeds exhibit exceptionally rapid growth rates and high carbon assimilation capacities, enabling them to absorb substantial quantities of CO_2 through photosynthesis. Although much of the fixed carbon is recycled within marine ecosystems, a significant fraction is exported to deep ocean waters and sediments, where it may remain stored for decades or even centuries [6]. Consequently, large-scale seaweed cultivation is increasingly recognized as an effective nature-based strategy for climate change mitigation while simultaneously supporting sustainable coastal development.

Seaweed forests also provide invaluable ecosystem services that extend beyond carbon capture. These underwater habitats function as biodiversity hotspots by offering food, shelter, breeding grounds, and nursery habitats for numerous marine organisms, including fish, crustaceans, mollusks, echinoderms, and marine mammals. Healthy kelp forests enhance fisheries productivity, stabilize coastal food webs, and improve ecosystem resilience against environmental disturbances [3]. Moreover, dense seaweed canopies reduce wave energy and coastal erosion, thereby protecting shorelines from storm surges and rising sea levels. Such ecosystem-based adaptation measures are becoming increasingly important as coastal communities worldwide face growing climate-related risks.

Algae also contribute significantly to ecological restoration and habitat recovery in degraded aquatic environments. In lakes and reservoirs affected by nutrient pollution, carefully managed algal cultivation systems can restore nutrient balance and improve dissolved oxygen levels. In coastal regions, seaweed restoration projects have demonstrated success in rehabilitating degraded marine habitats, increasing biodiversity, and enhancing water quality. The cultivation of integrated multi-trophic aquaculture (IMTA) systems—where seaweeds are grown alongside fish and shellfish—has further illustrated how algae can recycle dissolved nutrients, reduce aquaculture waste, and improve the environmental sustainability of marine food production systems [12].

Recent advances in algal biotechnology have further strengthened the environmental applications of algae. Researchers are integrating algal cultivation with

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carbon capture systems, wastewater treatment facilities, renewable energy production, and nutrient recycling technologies to develop closed-loop biorefineries that minimize waste generation while maximizing resource recovery. Artificial intelligence, remote sensing, and precision monitoring technologies are also being employed to optimize algal productivity and improve the efficiency of large-scale environmental restoration projects [28]. Such multidisciplinary innovations align closely with the United Nations Sustainable Development Goals (SDGs), particularly those related to climate action (SDG 13), clean water and sanitation (SDG 6), life below water (SDG 14), and responsible consumption and production (SDG 12).

Despite these promising developments, challenges remain regarding the large-scale implementation of algal restoration technologies, including cultivation costs, harvesting efficiency, seasonal variability, and ecological risk assessment. Nevertheless, continued research, technological innovation, and supportive policy frameworks are steadily overcoming these barriers. As governments and industries increasingly prioritize low-carbon and circular economy strategies, algae are expected to become central components of future environmental restoration programs [21].

In an era defined by climate uncertainty and environmental degradation, algae represent far more than simple aquatic organisms. Their extraordinary capacity to purify water, recycle nutrients, restore degraded ecosystems, support marine biodiversity, and capture atmospheric carbon establishes them as one of the most effective nature-based solutions for ecological restoration. Harnessing these remarkable biological capabilities will be essential for building resilient ecosystems and advancing a sustainable, climate-resilient future [24].

4. Green Bio-factories for a Sustainable Future

Beyond their ecological significance, algae have emerged as versatile green bio-factories capable of producing a wide array of high-value biomolecules and bioproducts. Their rapid growth rates, high photosynthetic efficiency, and ability to thrive on non-arable land using saline or wastewater make them sustainable alternatives to conventional agricultural and industrial resources. Advances in algal biotechnology, metabolic engineering, and biorefinery approaches have further expanded their commercial potential, positioning algae at the forefront of the global bioeconomy [29].

Among the most successful commercial applications of algae is their use as nutrient-rich functional foods and nutraceuticals. Microalgae such as *Spirulina* (*Arthrospira platensis*) and *Chlorella vulgaris* are excellent sources of high-quality protein (50–70% dry weight), essential amino acids, vitamins, minerals, polyunsaturated fatty acids, pigments, and antioxidants such as phycocyanin, chlorophyll, and carotenoids. These bioactive constituents have been associated with antioxidant, immunomodulatory, hypocholesterolemic, and anti-inflammatory activities, leading to their widespread use as dietary supplements and ingredients in functional foods [30].

Algae are also considered one of the most promising renewable feedstocks for third-generation biofuels. Lipid-rich microalgae can be converted into biodiesel, while their carbohydrate-rich biomass can be utilized for bioethanol, biogas, biohydrogen, and sustainable aviation fuels. Unlike terrestrial biofuel crops, algal cultivation requires substantially less freshwater and arable land and can utilize saline water, industrial wastewater, and carbon dioxide-rich flue gases, thereby minimizing competition with food production and enhancing resource-use efficiency [31]. Integrated algal biorefineries further improve economic feasibility by simultaneously producing biofuels alongside high-value co-products.

The pharmaceutical and biomedical sectors are also increasingly exploiting algae as sources of bioactive compounds. Algal metabolites—including polysaccharides, polyphenols, carotenoids, sterols, peptides, and sulfated compounds—have demonstrated antioxidant, antimicrobial, antiviral, anti-inflammatory, anticancer, and neuroprotective activities in experimental studies. These compounds are being investigated for applications in drug discovery, wound healing, tissue engineering, drug delivery systems, and cosmetic formulations, highlighting algae as an important reservoir of novel therapeutic molecules [31].

Collectively, these diverse applications underscore the transition of algae from simple aquatic organisms to multifunctional biological factories capable of supporting sustainable food systems, renewable energy production, and innovative healthcare solutions. As technological advancements continue to improve cultivation and downstream processing, algae are expected to play an increasingly important role in achieving a resilient and circular bioeconomy [32].

5. Supporting Sustainable Agriculture

Algal biotechnology is increasingly transforming modern agriculture by providing sustainable alternatives to conventional agrochemicals. Seaweed-derived biostimulants, obtained primarily from brown, red, and green macroalgae, are widely used to enhance seed germination, root development, nutrient uptake, photosynthetic efficiency, and crop yield. Rich in phytohormones, polysaccharides, amino acids, and micronutrients, these extracts also improve plant tolerance to abiotic stresses such as drought, salinity, heat, and nutrient deficiency, thereby enhancing crop resilience under changing climatic conditions [33].

Microalgae are also gaining prominence as biofertilizers because of their ability to improve soil fertility and promote beneficial microbial communities. Species such as *Chlorella*, *Scenedesmus*, and cyanobacteria enrich soils by supplying organic matter, nitrogen, phosphorus, vitamins, and growth-promoting metabolites while enhancing soil structure and water-holding capacity. Their application reduces dependence on synthetic fertilizers, lowers nutrient losses, and minimizes environmental pollution associated with excessive chemical inputs [34].

Furthermore, integrating algal biofertilizers and bio-stimulants into crop production supports regenerative agriculture and the circular bioeconomy by recycling nutrients and improving resource-use efficiency. As sustainable farming practices become increasingly important for ensuring global food security, algae-based agricultural inputs are emerging as environmentally friendly solutions for improving productivity while conserving soil health and ecosystem integrity [12].

6. Challenges and Future Perspectives

Despite their immense ecological and commercial potential, the large-scale deployment of algal technologies remains constrained by technical and economic challenges. Efficient cultivation requires precise control of environmental factors such as light intensity, temperature, nutrient availability, pH, and contamination, while harvesting and downstream processing of microalgal biomass continue to account for a significant proportion of production costs. Additionally, variability in biomass productivity and the energy-intensive extraction of valuable metabolites remain major barriers to commercial scalability [35].

Nevertheless, rapid advances in genetic engineering, synthetic biology, artificial intelligence (AI), photobioreactor design, and integrated biorefinery technologies are improving algal productivity, resource-use efficiency, and process economics. AI-assisted cultivation systems enable real-time optimization of growth conditions, while metabolic engineering is facilitating the development of high-yield algal strains tailored for biofuels, pharmaceuticals, and other high-value products. These innovations are expected to accelerate the transition of algae-based technologies from laboratory research to industrial application [36].

Looking ahead, algae are poised to become integral components of sustainable development strategies. Their integration into carbon capture systems, wastewater treatment plants, circular bioeconomy models, climate-smart agriculture, renewable energy production, and life-support systems for long-duration space missions highlights their extraordinary versatility. Continued investment in interdisciplinary research, supportive policy frameworks, and public–private partnerships will be essential to unlock the full potential of algae as a cornerstone of the global green economy [36].

7. Conclusion

Algae are far more than simple aquatic organisms; they are indispensable regulators of Earth's life-support systems. As major contributors to global oxygen production and natural carbon sequestration, they play a vital role in maintaining atmospheric balance, supporting aquatic biodiversity, and mitigating the impacts of climate change. Beyond their ecological significance, algae have emerged as versatile bioresources with applications spanning renewable energy, sustainable agriculture, environmental remediation, food and nutrition, and biopharmaceuticals. Their ability to simultaneously address multiple global challenges makes them a cornerstone of the emerging circular bioeconomy and a key component of future climate-resilient development.

As the world strives to achieve carbon neutrality and sustainable development, conserving natural algal ecosystems while accelerating innovations in algal biotechnology will be increasingly important. Continued investment in research, supportive policies, and responsible commercialization can unlock the full potential of algae as nature-based solutions for environmental restoration and green industrial transformation. Recognizing algae as the "green lungs" and "carbon warriors" of Earth is therefore not merely a metaphor but a scientific reality that underscores their indispensable contribution to planetary health and a sustainable future for generations to come.

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