https://doi.org/10.46344/JBINO.2026.v15i02.14

PIONEERING BIOTECHNOLOGICAL AND MICROBIAL INNOVATIONS FOR OPTIMIZED BIOMASS AND BIO PRODUCT SYNTHESIS IN MICROALGAE AND CYANOBACTERIA: INTEGRATING SUSTAINABLE STRATEGIES FOR ENHANCED SOIL AND WATER CONSERVATION.

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ABSTRACT

This review examines biotechnological and microbiological developments that optimize biomass and bio product synthesis in microalgae and cyanobacteria while incorporating sustainable soil and water conservation methods. We look at advanced genetic engineering and synthetic biology techniques that have improved the performance of strains by focusing on their metabolic pathways, including CRISPR/Cas systems and synthetic regulatory circuits. These innovations have increased biomass production and bio product yields from biofuels and bioplastics to high-value pharmaceuticals and enabled the creation of robust microbial consortia that support nutrient cycling and environmental remediation. The review also covers microalgae and cyanobacteria in environmental sustainability. Biological nitrogen fixation boosts soil fertility by providing bioavailable nitrogen without chemical fertilizers. Their ability to absorb extra nutrients, remediate contaminants, and collect carbon dioxide via photosynthesis makes these bacteria efficient wastewater treatment and water conservation options, reducing climate change. High cultivation and processing costs make large-scale application uneconomical. The study explores eco-friendly mass manufacturing and integrated bio-refinery models that use waste streams and renewable energy to cut costs and scale commercially. The assessment concludes with research priorities that emphasizes next-generation synthetic biology techniques, genetic engineering for greater yields, and sustainable processing advances. It requires interdisciplinary partnerships and supportive governmental frameworks to speed advanced biotechnology adoption. By connecting cutting-edge research to practical applications, these technologies could alter biomass and bioproduct synthesis, creating a circular bio economy and a robust foundation for sustainable agricultural and environmental practices.

Key words: Microalgae, Cyanobacteria, Biomass Production, Bio product Synthesis, Genetic Engineering, Synthetic Biology, Soil Conservation, Water Remediation, Sustainable Biotechnology,

1.INTRODUCTION

Microalgae and cyanobacteria create biofuels, pigments, and medications due to their metabolic flexibility, making them renewable resources. These organisms employ their photosynthetic system to convert atmospheric CO_2 into sustainable industrial feedstocks (Nawaz et al., 2024; Zou et al., 2020). Microorganisms replace chemical processes with less environmental impact (Nawaz et al., 2024). Climate change, rising energy needs, and decreasing soil and water conditions necessitate adaptable agricultural approaches. Climate change has raised demand for renewable energy and bio products, which reduce greenhouse gas emissions and fossil fuel use. Das et al. (2023). Microalgae and cyanobacterial activities in agricultural settings improve water and soil conservation (Farooq, 2023). The benefits demonstrate how sophisticated biotechnology links environmental sustainability and economic productivity. The research assesses microbiological and biotechnological improvements to increase microalgae and cyanobacteria biomass and bioproduct outputs. The research combines these advances with soil and water conservation methods. The evaluation helps researchers, industry executives, and policymakers understand process and genetic alterations and renewable resource growing methods. The research addresses the need for sustainable agriculture that reduces resource strain and promotes a circular bioeconomy. (Nawaz et al., 2024; Das, 2023).

2.Microalgae and Cyanobacteria as Biomass Sources

Microalgae and cyanobacteria are vital to ecological systems due to their photosynthetic ability and rapid growth. Light-powered microorganisms collect carbon dioxide and inorganic nutrients to generate biomass. Photosynthetic plants store chemical energy in biomass for later use. The biological features of microalgae and cyanobacteria make them attractive for biotechnology applications. These microbes flourish in freshwater, marine, and wastewater ecosystems, making them useful for bioremediation. They improve water quality by absorbing nutrients from wastewater and producing biomass for biofuels, animal feed, and bioproducts (Jabri et al., 2020; Qin et al., 2023). Their various metabolic capabilities allow them to extract important substances for use in food production, health products, and pharmaceuticals to address the growing demand for sustainable natural alternatives.

3.Types of Microalgae and Cyanobacteria

The many microalgae and cyanobacteria genera have different biotechnological benefits. The health food market favors Chlorella spp. and Spirulina (Arthrospira spp.) because they have high protein and necessary amino acids (Song et al., 2025; Rakhi et al., 2025). Haematococcus pluvialis astaxanthin is a strong antioxidant used in cosmetics and dietary supplements (Nishshanka et al., 2022). Nannochloropsis spp. and Phaeodactylum tricornutum are useful for biodiesel and omega-3 fatty acid production due to their high lipid content. The nitrogen-fixing ability of Anabaena and Nostoc cyanobacteria helps make the soil more fertile, which boosts crop production through biofertilization. The microalga Tetradesmus obliquus makes important substances and can adjust to various nutrient levels, which makes it suitable for producing large amounts of biomass. The diversity of microalgae and cyanobacteria shows their adaptability and potential industrial uses in energy, agriculture, and pharmaceuticals.

Table 1: Nutrient Requirements for Effective Microalgae Cultivation

Nutrient	**Role in Growth**	**Source/Concentration**	**References**
Carbon	Primary energy source	CO2, in gas or bicarbonate form	Pandya et al., 2023
Nitrogen	Essential for protein synthesis	Ammonium, Nitrates	Pandya et al., 2023; Nishshanka et al., 2022
Phosphorus	Key component of nucleic acids	Phosphate salts	Pandya et al., 2023
Potassium	Regulates osmotic balance	Potassium salts	Pandya et al., 2023
Magnesium	Enzyme co-factor	Magnesium sulfate	Pandya et al., 2023
Iron	Necessary for chlorophyll synthesis	Ferric salts, iron chelates	Pandya et al., 2023; Nishshanka et al., 2022

4.Applications of Biomass and Bioproducts

Several regions use micro algal and cyanobacterial biomass to achieve global sustainability goals. Energy creates biodiesel and bioethanol from microalgae biomass. Transesterification-based biodiesel production uses lipid-rich microalgae to produce FAMEs, which serve as engine fuels (Licata et al., 2025; Araújo et al., 2022). Innovative harvesting and ionic liquid extraction technologies improve lipid extraction efficiency and lower production costs (Tan et al., 2020; Parmar, 2023). Due to their protein and amino acid content, microalgae are suitable feed for cattle and aquaculture (Ummalyma et al., 2022; Li et al., 2020). The dual-purpose food production gear improves aquaculture water quality and nutrition. (Li et al., 2020). The production of bioplastics from micro algal biopolymers presents a sustainable plastic alternative to traditional petrochemical plastics. The production of biodegradable films together with other materials from biomass supports global sustainability targets (Ahmad et al., 2023; Bella, 2022). The pharmacological applications of micro algal extracts containing antioxidants show promise for nutraceuticals and medical goods (Hassan et al., 2022; Luca, 2021). Scientists conduct research on microalgae-derived biomaterials which include biodegradable adhesives and lubricants. Microalgae-derived oils have been proven to create sustainable green lubricants which demonstrate excellent tribological properties according to recent research (Farfán-Cabrera et al., 2022). Research on phycobiliproteins as functional food ingredients and natural food colorants expands the applications of microalgae. Microalgae and cyanobacteria address worldwide challenges through their diverse nature and ecological advantages which help solve climate change and ensure energy sustainability and food security. The high-value bioproduct generation and biomass output capacity of these organisms positions them as leaders in biotechnology.

5.Biotechnological Strategies for Optimizing Biomass and Bioproduct Production

The production of microalgae and cyanobacteria biomass and bioproduct synthesis depends heavily on genetic engineering and synthetic biology techniques. The advancements in biotechnology allow scientists to modify particular genes which results in higher production of biofuels and valuable chemicals and essential industrial molecules (Dhokane et al., 2023). The application of CRISPR/Cas9 genome editing techniques in recent research has demonstrated its ability to enhance metabolic gene expression while minimizing competing pathways to achieve increased productivity. The use of CRISPR/Cas9 gene editing technology enhances photosynthetic and carbon capture gene activities which results in increased plant biomass production. Scientists achieved higher photosynthetic microorganism growth and biomass yield by developing strains that express light harvesting and carbon absorption genes at elevated levels. Scientists have successfully engineered fast-growing cyanobacteria to process carbon more efficiently in their metabolic pathways which leads to better production of valuable compounds from CO_2 (Zhang et al., 2023). The method demonstrates that sustainable biomass production can occur through natural photosynthetic mechanisms. The synthetic biology modular systems enable both coordinated gene expression and direct genetic treatments. The engineered constructs contain multiple enzymes which produce valuable bioproducts including lipids and carotenoids through overexpression. The integration of regulatory circuits in recent research has enabled dynamic gene expression control through environmental stimuli to maximize growth and product generation (Li et al., 2025).Synthetic circuits increase bioproduct production and reduce host metabolic burden, improving system efficiency. Microbial consortia can improve bioproduct synthesis beyond single-strain engineering. To supplement metabolic capacity, heterotrophic bacteria and microalgae or cyanobacteria are grown together. Kuo et al. (2022) found that photosynthetic partners fix CO_2 and create oxygen, whereas heterotrophs transform secretory metabolites into valuable chemicals. As one species' metabolic byproducts become substrates for another, a closed-loop system that optimises resource use stabilises the production system (Hu et al., 2023). Recent research indicates that co-culture systems can boost biomass output, environmental tolerance, and target bioproduct yields (Hu et al., 2023). Multiplex genome editing, which modifies many loci simultaneously, is also being used to generate breeds with synergistic features. The disruption of negative regulatory pathways and the upregulation of favourable genes have led to cell factories with greatly increased output (Dhokane et al., 2023). Genetic changes, combined with optimised farming procedures, aid industrial scale-up. With precision genetic engineering and synthetic biology, microalgae and cyanobacteria are more efficient biomass platforms. Researchers are employing CRISPR/Cas9 to increase critical genes, alter photosynthesis and carbon capture, and create cooperative microbial groups to sustainably produce biofuels and bioproducts. These innovations improve energy and environmental sustainability in bio-based manufacturing.

6.Optimizing Growth Conditions:

Optimizing microalgae and cyanobacteria growth conditions in large-scale culture increases biomass production. These organisms depend on light intensity, temperature, pH, and nutrition availability for growth and productivity. Photosynthetic organisms need optimal lighting to accumulate biomass. Photosynthetic organisms grow with light intensity, quality, and duration. Modern photo bioreactors increase growth rates by improving light penetration and uniformity. Light management during cultivation decreases photo inhibition and maximizes biomass production. Yao et al. (2020), Zhang et al. (2021). Cell metabolism and enzymatic activities are equally affected by temperature. The optimal temperature for each microalgae or cyanobacteria species exists but different temperatures can decrease productivity. The management of growth conditions through temperature optimization leads to increased CO_2 fixation and biomass production which results in higher yields throughout cultivation (Bai et al., 2021). The biochemical stability of the culture medium requires optimal pH. The availability and solubility of nutrients in the culture medium depends on pH variations which affect growth rates. The implementation of automated pH monitoring and adjustment systems benefits large-scale businesses. The cultivation of microalgae and cyanobacteria requires optimal nutrient conditions to achieve effective results. The growth of biomass and cell development requires nitrogen, phosphorus and trace elements to be supplied in specific proportions. The use of agricultural runoff or wastewater nutrient recycling decreases production costs while increasing biomass output (Domenzain et al., 2025; Peng et al., 2024). The implementation of effective CO_2 sequestration solutions becomes essential for algae farming operations at industrial scale while optimizing growth conditions. The use of exhaust gas CO_2 in photo bioreactors simultaneously reduces greenhouse gas emissions while providing carbon for algae development. The implementation of enhanced CO_2 capture and absorption methods demonstrates the advantages of waste recycling and sustainable biomass manufacturing (Brooks & Alper, 2021). Optimizing growth parameters and CO_2 utilization makes large-scale microalgal farming more feasible while solving environmental problems related to carbon emissions.

7.Microbial Ecology in Microalgae and Cyanobacteria Production

7.1 Symbiotic Relationships and Co-cultivation:

Microbial ecology optimizes microalgae and cyanobacteria production through symbiotic partnerships and co-cultivation with bacteria and fungi. These microbial consortia boost growth, bioproduct output, and diversity. A major benefit of co-cultivation is microalgae and beneficial bacteria synergy. Microalgae can grow quicker with certain bacterial strains that improve nutrient absorption. Yin et al. (2022) found that Rhodobacter and Pseudomonas species release vitamins and chemicals that promote algal development. The bacteria use these interactions to convert atmospheric nitrogen into a form that microalgae can use for increased biomass production without needing additional nitrogen (Liu et al., 2022). Fungi create microbial consortia which benefit algae. The symbiotic bond between microalgae and mycorrhizal fungi enables better nutrient absorption and water storage which results in improved growth. Microalgae obtain phosphorus from fungal mycelia and organic carbon from photosynthetic processes (Chepurna et al., 2025). The mutualistic connection enables microalgae to endure drought conditions and nutrient deficiencies. The development of engineered microbial consortia has led to new industrial applications. The combination of microalgae and bacteria in mixed cultures produces greater biomass yields than single-species cultures because of their cooperative interactions. The production efficiency increases when researchers select particular bioproducts that combine different microbial groups because each species contributes its unique capabilities (Li et al., 2025).

7.2Microbial Interactions

The process of nitrogen fixation by cyanobacteria depends on the enzyme nitrogenizes which operates poorly in oxygen-rich environments to convert atmospheric nitrogen into ammonia. The nitrogen fixation process by cyanobacteria provides plants with accessible nitrogen which enhances soil fertility and reduces the requirement for chemical fertilizers. The nitrogen-fixing enzyme nitrogenase requires microtomic conditions to function which Nostoc and Anabaena establish through their heterocyst structures. The cells maintain nitrogenizes protection from oxygen even when they exist in oxygen-rich environments to enable nitrogen fixation. Research conducted in fields shows that using cyanobacterial biofertilizers leads to increased soil nitrogen and carbon content particularly in salt-affected and marginal areas. Devi et al. (2021) conducted these studies. Soil inoculation with nitrogen-fixing cyanobacteria leads to increased crop yields especially in rice cultivation areas. The addition of cyanobacteria to deep-water culture systems increased nitrogen content which subsequently decreased the requirement for manufactured nitrogen fertilizers. The nitrogen fixation process performed by cyanobacteria produces additional advantages for soil health. The photosynthetic organic matter together with polymers from cyanobacteria creates better soil structure and improved water retention properties. The process enhances soil health through nutrient cycling while creating a diverse and robust microbial community. The use of cyanobacterial biofertilizers presents a sustainable solution to synthetic fertilizers because they cause environmental damage and require significant energy resources (El-Seedi et al., 2023).

7.3Biological Nitrogen Fixation:

Cyanobacteria perform essential nitrogen fixation from air through ammonia production using nitrogenase enzyme which operates poorly in oxygen environments. The process enables plants to obtain usable nitrogen which enhances soil fertility while decreasing the need for chemical fertilizers. The nitrogen-fixing cells of Nostoc and Anabaena produce heterocyst's which create microoxic environments for nitrogenase operation. The cells maintain protection of nitrogenizes from oxygen exposure even when oxygen levels remain high in their environment. Field research shows that using cyanobacterial bio fertilizers leads to increased soil nitrogen and carbon content particularly in salt-affected and marginal land areas. Devi et al. (2021) conducted these studies. The application of nitrogen-fixing cyanobacteria to soil through inoculation enhances rice crop yields. The addition of cyanobacteria to deep-water culture systems increased nitrogen levels which reduced the requirement for artificial nitrogen fertilizers. The nitrogen fixation process performed by cyanobacteria produces additional advantages for soil health. The photosynthetic organic matter together with polymers from cyanobacteria enhances both soil structure and its ability to retain water. The process enhances soil health by creating diverse microbial communities which become stronger through nutrient cycling. The use of cyanobacterial bio fertilizers provides a sustainable replacement for synthetic fertilizers which cause environmental harm and consume energy according to El-Seedi et al. (2023).

8.Sustainable Biotechnology and Environmental Benefits

8.1Soil Conservation through Microalgal Applications

Cyanobacteria perform essential nitrogen fixation through the enzyme nitrogenase which operates poorly in oxygen-rich environments to convert atmospheric nitrogen into ammonia. The process enables plants to obtain usable nitrogen which enhances soil quality and decreases the requirement for chemical fertilizers. The nitrogen-fixing enzyme nitrogenase operates in Nostoc and Anabaena heterocyst's which create microtomic environments. The cells maintain nitrogenizes protection from oxygen in all environments to enable nitrogen fixation. Research conducted in fields demonstrates that cyanobacterial bio fertilizers enhance soil nitrogen and carbon content particularly in salt-affected and marginal land areas. Devi et al. (2021) conducted these studies. Soil inoculation with nitrogen-fixing cyanobacteria leads to increased crop yields especially in rice cultivation areas. The addition of cyanobacteria to deep-water culture systems increased nitrogen content in soil thus minimizing the requirement for manufactured nitrogen fertilizers. The nitrogen fixation process performed by cyanobacteria produces additional advantages for soil ecosystems. Photosynthetic organic matter together with polymers produced by cyanobacteria enhances both soil structure and its ability to retain water. The process enhances soil health by creating a diverse microbial community that strengthens its overall structure. The adoption of cyanobacterial bio fertilizers provides a sustainable solution to synthetic fertilizers because they cause environmental damage and require significant energy usage (El-Seedi et al., 2023).

Table 2: Microalgae Species and Their Applications

Microalgae Species	Key Product	Application Area	Yield Potential (ton/ha/year)	References
Haematococcus pluvialis	Astaxanthin	Nutraceuticals, Food	5–10	Nishshanka et al., 2022
Chlorella vulgaris	Protein, Lipids	Food supplements, Biofuel	10–15	Wu et al., 2024
Tisochrysis lutea	DHA, EPA	Pharmaceuticals, Aquaculture	4–8	Thurn et al., 2022
Nannochloropsis oceanica	Omega-3 fatty acids	Functional foods	3–6	Mahdieh, 2025
Spirulina (Arthrospira)	Phycocyanin	Dietary supplements	10–20	Deamici et al., 2022

8.2Water Conservation and Remediation

Sustainable water conservation and cleanup undergo transformation through the use of microalgae and cyanobacteria. The photosynthetic process enables these microorganisms to extract nutrients and pollutants from wastewater thus making them suitable alternatives to traditional water treatment systems. The bacteria remove nitrogen, phosphorus and organic pollutants from wastewater through three processes: biosorption, bioaccumulation and biodegradation. Microalgae inhibit eutrophication in aquatic settings by assimilation, improving water quality. The novel bio-based water conservation method grows microalgae in wastewater treatment facilities. Photo bioreactors remove pollutants and capture Coursing treated wastewater for agriculture, industry, or drinking reduces freshwater demand (Abo-Shady et al. (2023); González-Camejo, 2021). The biomass from these treatment systems can be used to make biofuels and fertilizers. Wastewater nutrients are recovered while creating a circular bio economy. Microalgae filter industrial and municipal wastewater due to their salt and pH tolerance (Burjus et al., 2020; Braglia, 2021). These bacteria are useful for decentralized wastewater treatment plants in water-scarce regions due to their adaptability and resistance. Algal biofilms improve pollutant removal and lower treatment costs.

Table 3: Wastewater Treatment Efficiency Using Microalgae

Study Reference	Wastewater Source	Microalgae Used	Removal Efficiency (%)	Remarks
Kabaivanova et al., 2022	Agricultural wastewater	Chlorella sp.	75	Effective CO2 fixation
Goh et al., 2022	Domestic sewage	Spirulina	80	Comprehensive nutrient recovery
Guimarães et al., 2024	Palm oil mill effluent	Nannochloropsis	70	Cost-effective for biofuel
Giri et al., 2023	Constructed wetlands	Chlorella sp.	78	Efficient phytoremediation

8.3Carbon Sequestration

Microalgae are crucial for carbon sequestration and climate change mitigation due to their rapid biomass production and CO_2 fixation. Photosynthesis by microorganisms converts atmospheric CO_2 into organic compounds, forming biological carbon storage systems. Pal et al. (2023) suggest that their fast growth and effective CO_2 absorption make them a viable alternative to expensive and energy-intensive carbon capture devices. The ability of microalgae to thrive under different environmental conditions enables them to cultivate on non-farmable lands by utilizing wastewater or saltwater resources. The system enables large-scale development of photo bioreactors and open ponds while minimizing competition with traditional agricultural practices. The controlled exposure of microalgae to high CO_2 concentrations from industrial flue gases or atmospheric sources enables them to capture more carbon according to Reisoglu & Aydın (2023). The trapped carbon in cellular biomass enables production of biofuels and bioplastics and other useful bio products which create a self-sustaining system that produces energy while decreasing greenhouse gas emissions. Techno-economic and life cycle studies indicate that microalgae-based carbon capture systems can reduce CO_2 emissions and generate renewable bioenergy in industrial operations. Microalgae efficiently convert CO_2 into biomass, reducing climatic impacts and supporting a circular economy model in bio refineries (Pal et al., 2023). By lowering surface temperatures and increasing oxygen production, micro algal cultivation improves local air quality and climate. Research on microalgae genetics and growing practices is currently improving CO_2 fixation rates. Metabolic engineering and optimal growth conditions allow scientists to increase microalgae strains' photosynthetic efficiency and carbon capture potential. The biological approach to CO_2 sequestration is promising compared to existing approaches, which have issues in cost, scalability, and long-term storage (Reisoglu & Aydın, 2023).

Table 4: Environmental Benefits of Microalgae Cultivation

Environmental Benefit	Impact	Supporting Evidence
CO2 Sequestration	Captures significant atmospheric CO2	Brettfeld et al., 2023; Sun et al., 2025
Nutrient Recovery from Wastewater	Removes nitrogen and phosphorus contaminants	Dammak et al., 2023; Schoeters et al., 2022
Biodiversity Support	Enhances local ecosystems	Maslaki & Kouchaksaraei, 2023
Reduction in Greenhouse Gas Emissions	Lowers carbon footprint in biofuel production	Mahdieh, 2025; Singh et al., 2023

9.Challenges and Future Directions

9.1Challenges in Biotechnological Implementation

Scaling up microalgae- and cyanobacteria-based biotechnologies from lab to commercial applications is difficult. Operational and capital expenditures are the greatest challenge for large-scale cultivation systems. Photobioreactors and open pond systems require complicated infrastructure and advanced control systems to handle light, temperature, mixing, and fertilizer supply (Geremia et al., 2021). Wastewater treatment systems affect biomass production and pollutant removal efficiency. Microalgae- and cyanobacteria-based biotechnologies have many challenges in scaling up from lab to commercial. High operational and capital costs plague large-scale growing systems. To manage light, temperature, mixing, and fertilizer in photo bioreactors and open pond systems, we need complicated setups and advanced control systems. When incorporated into wastewater treatment systems, this affects biomass production and pollutant removal efficiency. Contamination control is difficult. Contamination control is difficult. Keeping large-scale axenic cultures healthy is hard, and unwanted or competing microbes can reduce the growth of target micro algal or cyanobacterial strains, leading to inconsistent production. Open photo bioreactors have lower biomass density than closed ones, making process optimization challenging. Harvesting and drying the biomass is expensive because it involves energy-heavy and costly methods like centrifugation and chemical flocculation. Scaling up nutrient control, especially with wastewater streams, is difficult. Wastewater is a cost-effective nutrition supply that aids bioremediation, but its diverse compositions and concentrations necessitate specialized pretreatment procedures and adaptable growth conditions, making process standardization difficult (Morais et al., 2021). The conversion of biomass into high-value products, like biofuels and bioplastics, is not yet technologically mature or economically viable, requiring metabolic pathway optimization and bio refinery research. Genetically engineering strain selection and developing strong microbial consortia can improve contamination resistance and production. Innovative reactor designs, like photo bioreactors that maximize light utilization and manage growing conditions, are essential. Renewable energy sources and cost-effective harvesting technologies will also be needed to lower the process's energy footprint and economic costs. Finally, circular economy models that fully valorize waste streams into biofuels, bio fertilizers, and other products will enable sustainable, industrial-scale operations (Liberti et al., 2024; Wan et al., 2021).

Table 5: Microalgae Co-cultivation Benefits and Challenges

Co-cultivation Strategy	Benefits	Challenges	References
Microalgae and Bacteria synergy	Enhanced nutrient uptake and growth	Managing species interactions	González-González & de-Bashan, 2021
Microalgae with aquatic plants	Increased oxygenation and biomass production	Competition for light and nutrients	Kang et al., 2021
Combination with heterotrophs (yeast)	Improved carbon source utilization	Complexity in maintaining culture conditions	Wu et al., 2024

9.2Economic Viability:

The economic viability of microalgae- and cyanobacteria-based biotechnologies hinders their widespread commercialization. Challenges include high photo bioreactor, nutrient, water, and downstream processing costs. Dębowski et al. (2022) argue that high capital and operational expenses prohibit large-scale production and competitive pricing compared to fossil fuel systems and conventional agricultural products. Often, the cultivation medium accounts for up to 50% of the production budget, making micro algal bio products like biofuels and bioplastics less economically appealing (Sakarika et al., 2023). Integrating low-cost substrates into cultivation may reduce these expenditures. Industrial or agricultural wastewaters can be used as nutrient sources to reduce input costs and remediate waste (Usai et al., 2024). Producers can reduce raw material costs and wastewater treatment environmental costs by using readily available waste streams. Advanced reactor designs include high-efficiency photo bioreactors, and these biofilm-based systems may lower production costs. These systems can increase light penetration and biomass yield per unit area, enabling economies of scale for cost-effective operations (Ali et al., 2025). Metabolic engineering and genetic modification can also boost strain growth rates and productivities, lowering biomass production costs (Nawaz et al., 2024). Renewable energy and circular bio economy policies can also help solve these economic issues. Strategic public–private partnerships, targeted subsidies, and favorable regulatory frameworks would scale up microalgae-based production systems and enable market integration (Idoko et al., 2024). Sustained research together with supportive economic policies and innovation will help overcome financial barriers to achieve the complete potential of algae-based sustainable technologies.To increase yields, microalgae and cyanobacteria biotechnology need improved synthetic biology, eco-friendly mass manufacturing, and genetic engineering. Developing genome editing technologies that target metabolic pathways precisely is promising. Yang et al. (2024) report that CRISPR/Cas technology can insert large DNA segments and control genes. We need to develop improved approaches to produce more efficient, photosynthetic, and stress-resistant strains. Research should build synthetic biology platforms with standardized genetic circuits for bio product production. For microalgae and cyanobacteria, using automated DBTL cycles along with AI and machine learning tools helps predict and improve how their metabolism works (Chen et al., 2020). Researchers may swiftly design and grow strains that produce biofuels, bioplastics, and high-value chemicals using this technology. Sustainable large-scale bioreactor designs and bulk culture production show promise. The design of future industrial reactors must maximize light penetration, carbon dioxide collection, and nutrition usage while minimizing contamination risk and energy use (Wang et al., 2020). Modern farming, renewable energy, and trash recycling would form a closed-loop production system. Synthetic biologists, chemical engineers, systems biologists, and environmental scientists must collaborate to solve scale-up problems. Building new regulatory frameworks and resolving ethical concerns are crucial as laboratory-scale outcomes transition into commercial-scale activities. Future strain enhancement research must produce molecular methods and system-level discoveries that are economically and environmentally sustainable.

Table 6: Economic Feasibility of Microalgae Biofuel Production

Study Reference	Cost of Production (USD/liter)	Potential Yield (liters/year)	Economic Viability Assessment
Singh et al., 2023	2.50	10,000	High
Chen et al., 2023	1.80	15,000	Medium
Jalilian et al., 2025	3.00	7,500	Low

Conclusion

The review demonstrates how microalgae and cyanobacteria enable sustainable biomass and bio product synthesis through biotechnological advancements while preserving soil and water resources. Advanced synthetic biology tools together with genetic engineering allow scientists to make exact modifications of metabolic pathways which results in higher biomass production and better yields of valuable products such as biofuels and bioplastics and pharmaceuticals. The combination of different microbial species in microbial consortia enhances soil fertility and water quality by promoting beneficial species interactions which leads to improved process efficiency and resilience. These bacteria demonstrate their ability to generate energy while simultaneously cleaning the environment. The ability of these innovations to solve global problems sustainably makes them important. The carbon sequestration abilities of microalgae and cyanobacteria present a solution to reduce greenhouse gas emissions during a time when the world faces climate change alongside resource depletion and environmental deterioration. Their bioremediation and soil restoration methods directly address soil depletion and water contamination. Transforming these technologies from lab demonstrations to industrial applications requires reactor engineering, eco-friendly manufacturing, and metabolic engineering advancements. Future advancements require collaboration between synthetic biology, environmental engineering, and agronomy (Panke, 2020; CAΔAHOB et al., 2025). Develop stronger, more efficient genetic editing tools that fit strain optimization methods in future research. Automated design-build-test-learn cycles should improve synthetic biology systems and speed up genetic component and control system discoveries. To lower production costs and energy consumption while increasing product yields, eco-friendly mass culture methods should be enhanced using renewable energy sources and creative reactor designs. Policymakers and funding agencies should foster interdisciplinary research and develop regulatory settings that stimulate commercial adoption of these technologies. In conclusion, this review's advances usher in a new sustainable biotechnology era. Biotechnologies using microalgae and cyanobacteria can change how we produce renewable energy, clean the environment, and farm sustainably by addressing issues like scaling up, affordability, and environmental impact. Academics, industry, and government must collaborate to implement these ideas to ensure a resilient and sustainable economy and environment.

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