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Review

Advancements in Synthetic Biology for Enhancing Cyanobacterial Capabilities in Sustainable Plastic Production: A Green Horizon Perspective

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Abstract: This comprehensive review investigates the potential of cyanobacteria, particularly nitrogen-fixing strains, in addressing global challenges pertaining to plastic pollution and carbon emissions. By analyzing the distinctive characteristics of cyanobacteria, including their minimal growth requirements, high photosynthetic efficiency, and rapid growth rates, this study elucidates their crucial role in transforming carbon sequestration, biofuel generation, and biodegradable plastic production. The investigation emphasizes cyanobacteria's efficiency in photosynthesis, positioning them as optimal candidates for cost-effective bioplastic production with minimized land usage. Furthermore, the study explores their unconventional yet promising utilization in biodiesel production, mitigating environmental concerns such as sulfur emissions and the presence of aromatic hydrocarbons. The resulting biodiesel exhibits significant combustion potential, establishing cyanobacteria as a viable option for sustainable biofuel production. Through a comprehensive assessment of both achievements and challenges encountered during the commercialization process, this review offers valuable insights into the diverse contributions of cyanobacteria. Its objective is to provide guidance to researchers, policymakers, and industries interested in harnessing bio-inspired approaches for structural and sustainable applications, thereby advancing global efforts towards environmentally conscious plastic and biofuel production.

Keywords: cyanobacteria; biodegradable plastics; biofuel generation; commercialization pathway; environmental concerns; sustainable applications

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1. Introduction

The escalating levels of toxicants in the atmosphere, coupled with the excessive use of fossil fuels and plastic derivatives, have led to an unprecedented increase in the carbon footprint [1]. The persistent accumulation of non-degradable plastics, discarded in landfills, poses a significant environmental challenge with implications lasting over the next century [2]. This scenario has given rise to new threats to the Earth's ecosystems and the survival of living organisms [3]. Rapid climate change, exacerbated by the proliferation of billions of tons of plastic products, poses a serious global environmental hazard, impacting marine ecosystems and giving rise to phenomena such as the "plastisphere" [4,5]. The marine ecosystem faces severe consequences due to the accumulation of plastic debris, leading to the fragmentation of plastics into microplastics that infiltrate the food chain [6]. Additionally, the ongoing COVID-19 situation has contributed to an uncalculated surge in single-use plastics, adding to the environmental challenges. The depletion of fossil fuels and

the ensuing energy crisis pose a potential misbalance in the world economy and progress, adding further challenges to achieving environmental goals [7,8]. The plastic industry, consuming approximately 6% of the world's oil, is projected to grow up to 20% by 2050, highlighting the urgent need for sustainable alternatives [5,9]. Current assessments indicate a two-fold increase in global plastic production over the next 20 years, accompanied by substantial greenhouse gas emissions. The combustion of fossil fuels has led to a rise in atmospheric CO_2 levels, contributing to glacial mass loss and rising sea levels. The need to identify sustainable substrates that fulfill both energy demands and contribute to biodegradable plastics has never been more crucial [10–13]. Calculations for achieving carbon neutrality emphasize the necessity of reducing fossil fuel usage by 6–7 percent annually until 2030 [14]. Fossil fuel consumption, both for energy and commercial resources, incurs significant environmental and economic costs. This has spurred widespread interest in biofuels and bioplastics as sustainable alternatives [15,16]. While biofuels and bioplastics have been successfully produced from terrestrial plants, their cultivation competes for valuable agricultural land [17]. Cyanobacteria offer a promising alternative for bioplastic production and offer advantages over traditional bacteria and yeast. Their ability to use sunlight to generate energy and convert atmospheric CO_2 directly into organic compounds makes them more energy-efficient and environmentally friendly. Cyanobacteria can be genetically engineered to produce various bioplastics, require minimal nutrients, and are scalable for large-scale production. In contrast to bacterial cultivation, which often involves higher costs and energy-intensive processes, cyanobacteria offer a more economical approach to the sustainable production of bioplastics [16].

Cyanobacteria, often overlooked in the context of biofuel and bioplastic production, are now gaining attention due to their potential to efficiently sequester atmospheric CO_2 [18]. Common cyanobacteria species such as *Anabaena* and *Synechocystis* have demonstrated their ability to produce industrial compounds, including biofuels and bioplastics [19]. Compared to other organisms used for similar purposes, such as eukaryotic algae and land plants, cyanobacteria offer several advantages. They have a high specific growth rate, can thrive in adverse conditions such as salt water and barren land, and have the ability to fix atmospheric nitrogen, reducing the need for nitrogen fertilizers. In addition, cyanobacteria are easier to genetically manipulate, allowing more efficient optimization of metabolic pathways for the production of biofuels and bioplastics. Their abundant fatty acid and oil content, as well as other active metabolites, make them an excellent alternative for the sustainable production of these industrial compounds. The biofixation efficiency of cyanobacteria is estimated to be approximately 10-fold higher than that of terrestrial plants [20,21]. The dynamic metabolic versatility of cyanobacteria presents an opportunity to overcome challenges associated with biofuel and bioplastic production [22]. Genetic engineering and targeted genetic modulations are being explored to enhance cyanobacterial strains for increased yield [23]. This review paper aims to shed light on the potential of cyanobacteria as a green sustainable methodology for biofuel and bioplastic production. It explores the genetic engineering approaches to enhance their yield and addresses the scope and constraints related to large-scale industrial production. The study underscores the urgent need to replace fossil fuel substrates with environmentally friendly alternatives and presents cyanobacteria as a promising step toward sustainability in biofuels and bioplastics.

2. Synthetic Biology Strategies for Enhancing Cyanobacterial Plastic Production

Synthetic biology methodologies have played a pivotal role in propelling the capacity of cyanobacteria for sustainable plastic production [24]. Through the utilization of techniques grounded in genetic manipulation and metabolic engineering, investigators have endeavored to refine cyanobacterial metabolic pathways to augment the synthesis of plastic precursors [25]. The application of synthetic biology tools, exemplified by CRISPR-Cas9-mediated genome editing and homologous recombination, facilitates meticulous manipulation of cyanobacterial genetic material [26]. By integrating exogenous genetic elements encoding plastic biosynthesis enzymes and intricately adjusting endogenous

regulatory mechanisms, cyanobacterial strains exhibiting augmented plastic production capacities have been engineered [27]. Synthetic biology methodologies, exemplified by CRISPR-Cas9-mediated genome editing and homologous recombination, play a pivotal role in the genetic manipulation of cyanobacteria [28]. Metabolic engineering strategies are geared towards orchestrating cyanobacterial metabolism to facilitate the biosynthesis of plastic precursors [29]. This entails precise modulation of enzymatic activities and pathway flux to enhance the generation of key carbon intermediates crucial for polymer synthesis, notably acetyl-CoA and malonyl-CoA [30]. Moreover, the optimization of growth conditions, encompassing parameters such as light intensity, carbon source availability, and nutrient composition, serves to further bolster the accumulation of plastic precursors within cyanobacterial cells [31]. Pathway engineering assumes a central role in the meticulous design of customized biosynthetic pathways optimized for proficient polymer synthesis [32]. Through the deliberate engineering of synthetic gene circuits and genetic constructs, the orchestration of enzymatic activities and metabolic flux is achieved, thereby establishing a foundational framework for the intricate machinery of cellular plastic production [33]. Despite significant advancements, persistent challenges encompass heterologous pathway expression and metabolic burden [34]. Future research endeavors are directed toward surmounting these obstacles through the utilization of sophisticated synthetic biology tools and a comprehensive comprehension of cyanobacterial physiology [35]. This collaborative endeavor is directed towards fully harnessing the inherent potential of cyanobacteria as eco-friendly platforms for plastic synthesis [36].

3. Role of Cyanobacteria in Carbon Sequestration

Cyanobacteria, commonly known as blue-green algae, assume a pivotal role in carbon sequestration, a process crucial for mitigating climate change by capturing and storing carbon dioxide (CO_2) from the atmosphere [37–39]. Synthetic biology has shown great potential in artificially constructing new CO_2 assimilation pathways, and important research progress has been made in improving the carboxylation activity of the Rubisco enzyme, introducing a CO_2 concentration mechanism, reducing carbon loss, and reducing photorespiration (Figure 1). These microscopic photosynthetic organisms engage in oxygenic photosynthesis, harnessing sunlight to convert carbon dioxide and water into organic compounds such as carbohydrates while releasing oxygen [40]. This photosynthetic activity enables cyanobacteria to act as primary producers and create a carbon sink in the form of biomass. Carbon fixation, a process wherein atmospheric CO_2 is incorporated into organic molecules, is a fundamental step in their carbon sequestration mechanism [41]. Cyanobacteria often form dense microbial mats and biofilms in aquatic environments, providing protective niches where organic material accumulates and becomes buried in sediment layers [42]. Some cyanobacteria contribute to carbonate precipitation, forming calcium carbonate ($CaCO_3$), which aids in long-term carbon storage [43]. Additionally, the capacity of cyanobacteria to induce algal blooms and subsequent sedimentation enhances the sequestration of carbon in both aquatic and terrestrial ecosystems [44]. A large-scale study across the Loess Plateau in China found that the total ecosystem carbon stock was 2.8 Pg, with 30% stored in soil (0–20 cm), 53% in above-ground biomass, and 17% in below-ground biomass [45]. This study demonstrates the significant carbon sequestration potential of large ecosystems. In symbiotic relationships with plants, cyanobacteria further enrich soils with organic matter, promoting carbon storage [46]. The global impact of cyanobacteria in regulating atmospheric CO_2 levels underscores their significance in addressing climate change through effective carbon sequestration mechanisms [47].

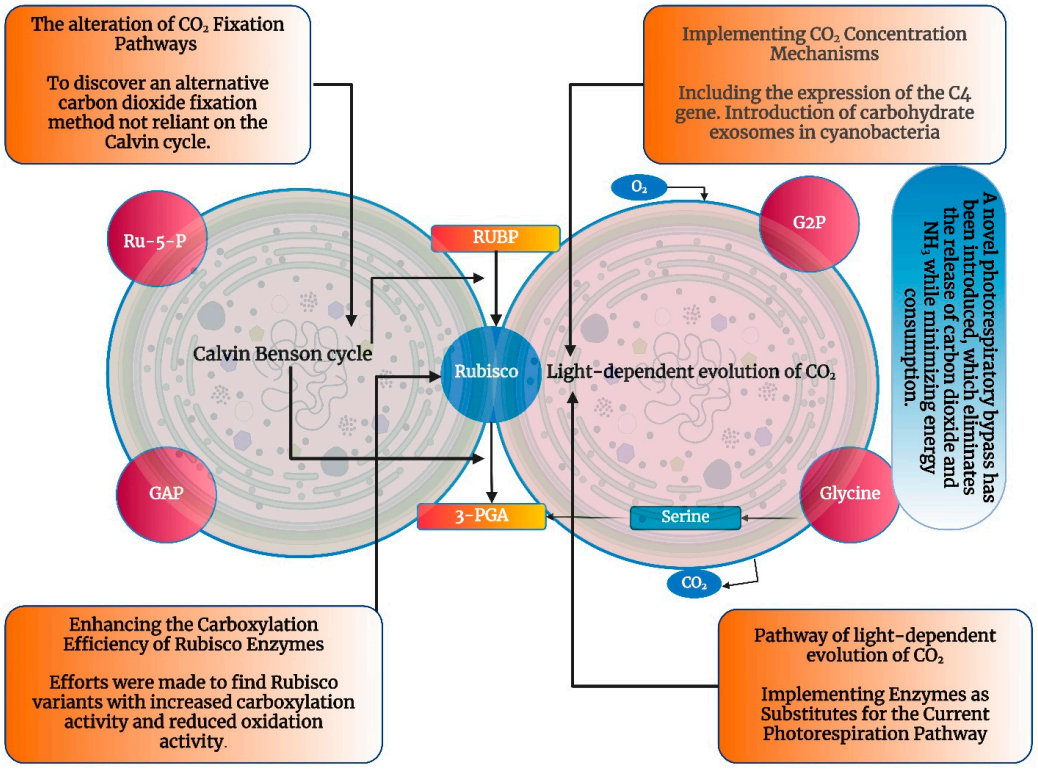

Figure 1. Engineering photosynthesis for increased carbon assimilation.

3.1. Cyanobacteria as Photosynthetic Prokaryotes

Cyanobacteria, classified as photosynthetic prokaryotes, represent a unique group of microorganisms with a remarkable capacity for oxygenic photosynthesis [48]. Unlike eukaryotic algae and plants, cyanobacteria lack membrane-bound organelles, such as chloroplasts, and their genetic material is housed in a nucleoid region within the cell [49]. Nonetheless, they share the fundamental photosynthetic machinery with higher plants [50]. These microorganisms harness sunlight to drive the conversion of carbon dioxide and water into organic compounds, generating energy-rich molecules such as carbohydrates [51]. The photosynthetic pigments, including chlorophyll-a, phycocyanin, and phycoerythrin, allow cyanobacteria to capture light across a broad spectrum, enabling them to thrive in various environments, from freshwater to marine ecosystems [52]. The thylakoid membranes within their cells serve as the sites for the light-dependent reactions of photosynthesis [53]. Cyanobacteria exhibit a unique ability among prokaryotes to produce oxygen during photosynthesis, a process that played a crucial role in shaping Earth's early atmosphere [54]. Their evolutionary significance is underscored by their role as primary producers, contributing substantially to global carbon fixation and the oxygenation of the atmosphere [55]. Moreover, cyanobacteria form diverse morphologies, ranging from unicellular to filamentous and colonial forms, allowing them to adapt to a wide range of ecological niches [56]. In addition to their role in carbon cycling, some cyanobacteria possess nitrogen-fixing capabilities, further influencing nutrient dynamics in ecosystems [46]. Overall, cyanobacteria's role as photosynthetic prokaryotes is integral to ecological processes, with implications for global biogeochemical cycles and the understanding of the evolution of photosynthesis in the context of early life on Earth [57].

3.2. Unique Attributes: Minimal Growth Requirements, High Photosynthetic Efficiency, and Rapid Growth Rates

Cyanobacteria possess a suite of unique attributes that collectively contribute to their ecological success and environmental impact [58]. Their minimal growth requirements set them apart, allowing them to thrive in environments with limited nutrients [59]. Cyanobac-

teria can colonize diverse habitats, ranging from nutrient-poor soils to oligotrophic aquatic ecosystems, showcasing their adaptability to varying ecological conditions [60]. This adaptability is partly attributed to their ability to fix atmospheric nitrogen, a crucial nutrient often limiting in terrestrial and aquatic ecosystems [61]. By converting atmospheric nitrogen into forms usable by other organisms, cyanobacteria play a pivotal role in nutrient cycling and ecosystem fertility. The high photosynthetic efficiency of cyanobacteria is another distinctive feature that enhances their ecological significance [46,62]. Their photosynthetic pigments, particularly chlorophyll-a along with phycocyanin and phycoerythrin, allow them to absorb light efficiently across a broad spectrum. This adaptation enables cyanobacteria to harness solar energy effectively and convert it into chemical energy through oxygenic photosynthesis [63]. This process not only supports their own growth but also contributes to the primary production of organic compounds in ecosystems, forming the basis of food webs [64]. Rapid growth rates further characterize cyanobacteria, and this ability has both ecological implications and applications. In recent years, with the rapid growth of high-throughput sequencing technology, more and more cyanobacterial genomes have been sequenced and analyzed, which has made the overall understanding of cyanobacterial genome size more comprehensive and accurate [65,66]. From a scientific standpoint, there exists a dearth of research regarding the copy number of cyanobacterial genomes in comparison to other areas of study. The relevant studies on cyanobacterial genome copies that have been reported so far are summarized in (Table 1). In favorable conditions, cyanobacteria can undergo exponential growth, leading to the formation of visible algal blooms [67]. While such blooms can have detrimental effects on water quality and ecosystems, the rapid growth of cyanobacteria can also be harnessed for beneficial purposes [68]. Researchers explore the potential of cyanobacteria in biotechnological applications, such as biofuel production and wastewater treatment, leveraging their ability to proliferate rapidly under controlled conditions [69].

The intricate interplay of minimal growth requirements, high photosynthetic efficiency, and rapid growth rates underscores the ecological versatility of cyanobacteria [70]. Their contributions to nutrient cycling, carbon sequestration, and their ability to respond dynamically to environmental changes make them integral components of ecosystems worldwide. Moreover, understanding these unique attributes offers insights into the evolutionary success of cyanobacteria and their pivotal role in shaping the dynamics of the biosphere [71,72].

Table 1. Exploring ploidy levels and key parameters in cyanobacterial species.

Species	Temperature (°C)	Time (h)	Genome Size (Mb)	Genome Copy No.	References
Anabaena cylindrica	28	18.7	–	25	[73]
Anabaena variabilis	30	–	7.1	5–8	[74]
1450/10 Microcystis aeruginosa	28	stat.ph. [a]	–	1–10	[75]
Anabaena sp. *Strain PCC 7120*	28	–	7.2	8.2	[76]
Prochlorococcus	–	–	1.7	–	[77]
Synechococcus elongatus PCC 7942	29	26	2.7	3.7/3.4	[78]
Synechococcus elongatus PCC 6301)	35	10 to >50	2.9	2–7 to >1–2 [d]	[79]
Synechococcus sp. (*strain WH7803*)	26	–	2.5	3.7 [e]	[78]
Synechococcus sp. *Strain WH7803*	23	–	2.3	2–6 [c]	[80]
Parasynechococcus subtropicalis WH 7805	26	17	2.5	1 [e]	[80]
Synechococcus sp. *WH 8101*	27	15	3.3	1 [e]	[81]
Synechocystis sp. *PCC 6803*	23	23	3.7	215/56/59 [c]	[78]
Synechocystis sp. *PCC 6803*	22	22	3.8	143/46/47 [c]	[78]
Synechocystis sp. *PCC 6803*	31	15–24	3.9	16	[82]
Trichodesmium erythraeumIMS101	26	LDC [b]	7.77	700	[83]

[a] Stationary stage; [b] blight-dark period; [c] Log growth phase/linear phase/stationary phase; [d] Longer doubling time correlates with reduced genome copy number. [e]. Derived from comparing the fluorescent chromosome band and genome size of PCC 6301.

3.3. Lipid Content in Thylakoid Membranes and Its Significance

The lipid content within the thylakoid membranes of cyanobacteria represents a highly nuanced and critical aspect of their cellular architecture and functional dynamics [84]. Thylakoid membranes, situated within the chloroplasts of cyanobacteria, serve as the primary site for the execution of photosynthesis, a complex process involving the conversion of light energy into chemical energy. The diverse array of lipids presents in these membranes, including phospholipids, glycolipids, and sulfolipids, collaboratively contributes to the structural stability, organization, and adaptability of the photosynthetic machinery [85]. Phospholipids, with phosphatidylglycerol being a prominent constituent, are instrumental in anchoring and stabilizing photosynthetic protein complexes within the thylakoid membrane [86]. This lipid matrix ensures the ordered arrangement of components such as light-harvesting complexes and reaction centers, creating an optimal environment for the efficient flow of electrons during the light-dependent reactions of photosynthesis [87]. The spatial arrangement of these lipids, along with their interaction with protein complexes, is finely tuned to achieve the intricate dance of energy transfer within the thylakoid membrane [88]. Glycolipids, specifically monogalactosyldiacylglycerol (MGDG) and digalactosyldiacylglycerol (DGDG), contribute to the structural dynamics of thylakoid membranes and play a pivotal role in the organization of photosynthetic pigments [89]. These glycolipids encapsulate chlorophyll molecules, creating a specialized microenvironment that facilitates light absorption and energy transfer. The fluidity and flexibility of thylakoid membranes, crucial for their adaptability to changing environmental conditions, are influenced by the composition and arrangement of these glycolipids. This flexibility is vital for the optimization of photosynthetic efficiency, allowing cyanobacteria to acclimate to varying light intensities and other environmental factors [90–92].

Beyond their structural roles, the lipids within thylakoid membranes contribute to the resilience of cyanobacteria in the face of environmental stresses [93]. The presence of polyunsaturated fatty acids in these lipids acts as a buffer against oxidative stress generated during photosynthesis [94]. Cyanobacteria, often exposed to high light intensities and fluctuating temperatures, employ these lipids as a form of protection against reactive oxygen species [95]. The unsaturation of fatty acids enhances the fluidity and integrity of thylakoid membranes, contributing to the overall stress tolerance of cyanobacteria [96,97]. The complex relationship between the lipid makeup of thylakoid membranes and the physiological reactions of cyanobacteria highlights the evolutionary adaptations these organisms have undergone over extended periods [98]. This understanding not only enriches our comprehension of fundamental cellular processes but also has practical implications [99]. Manipulating lipid metabolism within thylakoid membranes holds potential for biotechnological applications, such as engineering cyanobacteria for enhanced biofuel production, stress resistance, or other tailored functionalities. Fundamentally, the lipid composition of thylakoid membranes plays a crucial role in governing the comprehensive operation and adaptability of cyanobacteria, thereby influencing their ecological prowess and prospective applications in biotechnology [28,100].

4. Cyanobacteria's Contribution to Biofuel Production

Cyanobacteria's contribution to biofuel production is a field of burgeoning research and innovation, presenting a sustainable approach to meet the global demand for renewable energy [101]. These photosynthetic microorganisms possess distinctive characteristics that make them particularly attractive for biofuel applications [102]. One of the key features is their high lipid content, especially triacylglycerols (TAGs), which serve as valuable precursors for biodiesel production [103]. Researchers have been exploring ways to enhance lipid accumulation in cyanobacteria by adjusting growth conditions, nutrient availability, and light exposure [104]. Genetic engineering techniques are also being employed to tailor cyanobacterial strains for increased biofuel productivity. In addition to biodiesel, cyanobacteria exhibit the potential for biohydrogen production through a process known as hydrogen photoproduction [105]. This process involves the direct

conversion of solar energy into molecular hydrogen, offering a clean and sustainable alternative to traditional hydrogen production methods [106]. Cyanobacteria capable of biohydrogen production, such as certain strains of Anabaena and Synechocystis, are being investigated for their feasibility in large-scale biofuel applications [107]. Cyanobacteria's adaptability to diverse environmental conditions further enhances their appeal for biofuel production. These microorganisms can thrive in various ecosystems, including saline environments and wastewater, demonstrating their potential to utilize marginal lands unsuitable for conventional agriculture [108,109]. Their relatively rapid growth rates and ability to fix atmospheric carbon dioxide contribute to their efficiency in converting solar energy and carbon into biomass, laying the groundwork for sustainable biofuel feedstock production [110]. Ongoing research aims to optimize cyanobacterial cultivation techniques, exploring novel photobioreactor designs, nutrient management strategies, and synthetic biology approaches. By fine-tuning these parameters, scientists seek to maximize biofuel yields and establish economically viable and environmentally friendly production systems. Moreover, advancements in genetic engineering offer the potential to tailor cyanobacteria for specific biofuel traits, enhancing their overall productivity and resilience [111,112].

As the global community amplifies endeavors toward transitioning to renewable energy sources, the utilization of cyanobacteria in biofuel production emerges as a promising prospect. The sustainable and carbon-neutral attributes of cyanobacterial biofuels position them as pivotal entities in the pursuit of cleaner energy solutions. Despite persistent obstacles, ongoing scientific investigations and advancements in technology aimed at exploiting the potential of cyanobacteria emphasize their significance in influencing the course of biofuel production and promoting a more environmentally sustainable energy landscape.

4.1. Overview of Biodiesel Production from Cyanobacteria

Biodiesel production from cyanobacteria represents a multifaceted and dynamic process that integrates various scientific disciplines, from microbiology and biochemistry to engineering [113]. The journey begins with the careful cultivation of cyanobacterial strains under controlled conditions to optimize their growth and lipid accumulation. This involves fine-tuning parameters such as light intensity, temperature, nutrient availability, and carbon dioxide concentration [114]. However, microalgae production is generally expensive compared to crops, photosynthetic growth requires light, carbon dioxide, water, and inorganic salts. The temperature is generally maintained between 20 and 30 °C. To minimize costs, biodiesel production can ignore seasonal and day-night changes in light and rely on natural light. In the culture process of microalgae, the inorganic elements required for their cell growth include nitrogen (N), phosphorus (P), iron (Fe), and in some cases the appropriate amount of silicon (Si), which must also be supplemented. The minimum requirements of these elements can be determined by the approximate molecular formula expressed by microalgae, namely $CO_{0.48}$ $H_{1.83}$ $N_{0.11}$ $P_{0.01}$. The formula is based on Grobelaar's calculations [115]. Nutrients such as phosphorus, must be supplied in excess because the absorption of certain metal ions is coupled with phosphate ion absorption, and therefore, not all supplemental phosphorus is available to organisms. Grima et al. [116] successfully cultured microalgae using seawater supplemented with commercial nitrate, phosphate fertilizers, and several other nutrients, and seawater has become an increasingly common medium for marine microalgae. The theoretical production process of biodiesel from microalgae is shown in [Figure 2] [117]. Once the cyanobacterial biomass reaches an optimum lipid content, the next critical step is lipid extraction. Various methods are employed for this purpose, each with its own set of advantages and challenges [118]. Traditional solvent extraction methods involve the use of organic solvents to dissolve lipids, while mechanical pressing physically separates lipids from the biomass [119]. Additionally, emerging technologies such as supercritical fluid extraction are being explored for their potential to provide more efficient and environmentally friendly lipid extraction. Following lipid extraction, the isolated triacylglycerols (TAGs) undergo transesterification, a chemical process that transforms them into biodiesel [120]. In this process, the TAGs react with

an alcohol, usually methanol or ethanol, in the presence of a catalyst. The result is the production of biodiesel and glycerol as a byproduct [121]. Catalyst selection, reaction conditions, and the overall efficiency of the transesterification process are crucial factors that influence the quality and yield of biodiesel [122]. The advantages of using cyanobacteria for biodiesel production are multifaceted. Their photosynthetic efficiency allows them to directly convert sunlight and carbon dioxide into lipids, making them highly efficient biofuel producers [123]. Furthermore, their ability to thrive in diverse environments, including non-arable land and wastewater, mitigates concerns related to competition with food crops for cultivation space. This aligns with the broader goal of developing sustainable and environmentally friendly biofuel feedstocks [109,124].

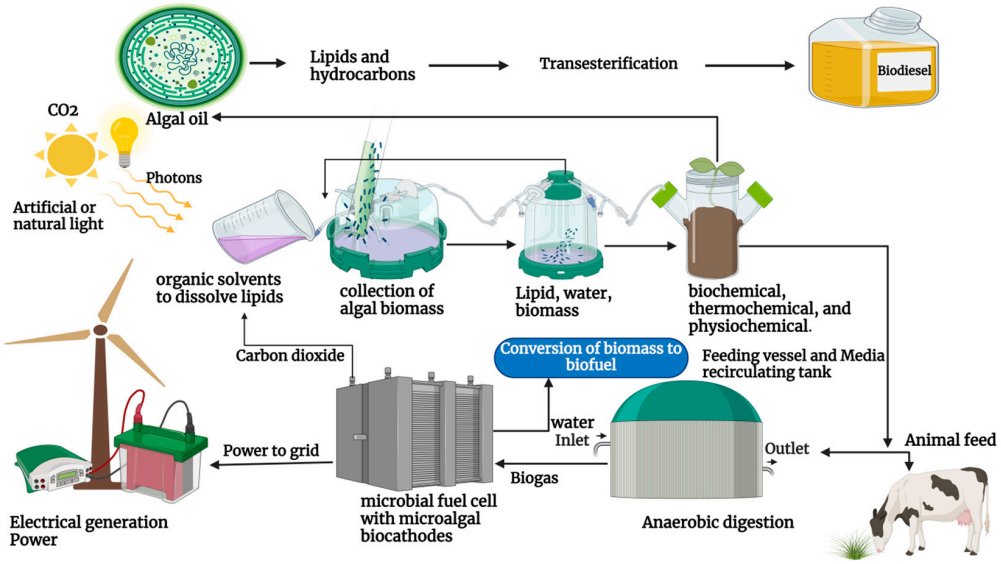

Figure 2. Life-cycle assessment of biodiesel production from microalgae.

Despite the favorable characteristics displayed in cyanobacterial biodiesel production, persistent challenges persist. Ongoing scientific endeavors are focused on optimizing cultivation parameters, refining lipid extraction methodologies, and tackling economic and scalability hurdles. Additionally, researchers are exploring co-cultivation strategies, nutrient recycling techniques, and potential synergies with other biotechnological processes to augment efficiency and sustainability. As advancements continue, cyanobacterial biodiesel production underscores the inventive exploitation of natural reservoirs for sustainable energy solutions. The integration of biological research, engineering, and environmental science in this domain offers prospects for substantially advancing the global quest for renewable and environmentally sound energy alternatives.

4.2. Mitigation of Toxic Sulfur Release

The mitigation of toxic sulfur release in the context of biodiesel production from cyanobacteria is a multifaceted challenge that demands careful consideration and strategic intervention throughout the production process [125]. During transesterification, a critical step in biodiesel production, the reaction between triacylglycerols (TAGs) and alcohol is facilitated by catalysts, often sodium hydroxide or potassium hydroxide [126]. However, the potential release of toxic sulfur-containing compounds, stemming from impurities in the catalyst or contaminants in the starting materials, poses environmental and product quality concerns [127]. To tackle these challenges, scientists are vigorously investigating catalyst-centric approaches. Primarily, the identification of top-tier catalysts with low sulfur content is paramount [128]. Furthermore, rigorous purification processes are implemented to ensure that the catalysts used in transesterification are free from sulfur impurities. Investigating alternative catalysts, such as solid catalysts or enzymes, which inherently possess lower

sulfur content, is also gaining traction [129]. These approaches collectively aim to reduce the introduction of sulfur into the biodiesel synthesis process, promoting cleaner and more sustainable production. Beyond catalyst-related strategies, researchers are examining the influence of feedstock selection and cultivation conditions on sulfur content [130]. The choice of cyanobacterial strains and optimization of growth conditions can impact the lipid composition and, consequently, the sulfur content in the resulting biodiesel [131]. Post-transesterification processes are integral to further purify biodiesel and diminish sulfur impurities. Washing and distillation are among the techniques employed to enhance the overall quality of biodiesel [132]. These purification steps contribute to meeting stringent fuel standards, ensuring that the final biodiesel product is environmentally compliant and suitable for widespread use [133].

The challenge of mitigating toxic sulfur release is not only a technical concern but also a regulatory and environmental imperative. Researchers and engineers are actively engaged in refining these processes to align with global biodiesel quality standards and environmental regulations [134]. Continuous advancements in alternative catalysts, feedstock optimization, and post-transesterification purification techniques underscore the commitment to producing high-quality biodiesel from cyanobacteria while minimizing the potential negative impacts associated with sulfur-containing compounds [135]. As the scientific discipline advances, addressing the emission of toxic sulfur emerges as a pivotal component within the overarching goal of promoting cyanobacterial biodiesel as a viable, eco-conscious alternative. Employing a comprehensive strategy encompassing catalyst optimization, efficient feedstock handling, and rigorous post-production refining, the biodiesel sector endeavors to foster a greener energy paradigm while diminishing reliance on conventional fossil fuel sources.

4.3. Reduction of Aromatic Hydrocarbons

The reduction of aromatic hydrocarbons is a key consideration in the production of biodiesel from cyanobacteria, particularly as it pertains to improving the fuel's combustion characteristics and meeting stringent environmental standards [136]. Aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylene (BTEX), are undesirable components due to their association with toxicity, low cetane numbers, and elevated emissions during combustion [137]. Addressing the presence of aromatic hydrocarbons in biodiesel derived from cyanobacteria involves strategic interventions throughout the production process [123]. Cyanobacterial strains and cultivation conditions significantly influence the composition of lipids, including the fatty acid profile in the resulting biodiesel. Researchers are actively exploring the manipulation of these factors to optimize the fuel's properties [138]. By selecting cyanobacterial strains with lower aromatic hydrocarbon content and fine-tuning growth conditions, efforts are underway to mitigate the incorporation of undesirable components into the biodiesel matrix [139]. The transesterification process itself can be tailored to minimize the formation of aromatic hydrocarbons [140]. The choice of alcohol for transesterification, such as methanol or ethanol, can impact the final composition of the biodiesel, and optimizing this parameter is part of the ongoing research efforts [141]. Post-transesterification purification procedures, including fractional distillation, liquid-liquid extraction, and adsorption, are pivotal for diminishing aromatic hydrocarbons in biodiesel, thereby enhancing its combustion attributes and environmental suitability through the selective elimination of undesired constituents [142]. For a variety of nitroaromatic hydrocarbons and their halogenated derivatives with different structures, microorganisms can evolve corresponding metabolic pathways in a short period, and show strong adaptability and diversity of metabolic capacity. Compared with the non-specific metabolism and transformation of fungi and anaerobic bacteria, bacteria can often use nitroaromatic compounds as the only carbon source, nitrogen source, and energy growth, which provides greater advantages in biological management and bioreaction of pollutants. Microbiologists have isolated many bacteria capable of degrading nitro-aromatic pollutants (Table 2).

Table 2. Degradation of nitroaromatic compounds and their chlorinated derivatives by different microorganisms.

Common Synonyms	Strains	Initiate Enzymes	Ring-Cleavage Substrates
aniline	*P. pseudoalcaligenes* JS45	NR	o-Aminopheno
2-nitrochlorobenzene	*P. putida* OCNB-1	NR	1-Chloro-2,3-dihydroxybenzene
4-Chloro-1-nitrobenzene	*P. putida* ZWL73	NR	(4-CAP)
2-hydroxynitrobenzene	*P. putida* B2,	One-component Monooxygenases	pyrocatechol
3-Nitrophenol (*m*-)	*P. putida* B2	NR	1,2,4-Benzenetriol
p-nitrophenol	*Pseudomonas* sp. WBC-3	One-component Monooxygenases	benzene-1,4-diol
2-4-DNP	*R. erythropolis* HL24-1 *R. erythropolis* HL24-2	–	(*anionic ç-complex*)
2-6-DNP	*C. necator* JMP134	–	3-Nitroquinolin-4-ol
Picric acid	*Nocardioides* sp. CB22-2 *R. erythropolis* HLPM-1	–	(*anionic ç-complex*)
nitrofungin	*Burkholderia* sp. strain SJ98 *Burkholderia* sp. RKJ 800 *Arthrobacter* sp. SJCon	One-component Monooxygenases	2-Chlorohydroquinone *C6H5ClO2*
4C2NP	*Exiguobacterium* sp. PMA	NR	2-Amino-1-hydroxybenzene
2C5NP	*C. pinatubonensis* JMP134	NR	*2-Aminohydroquinone hydrobromide*
2,6-Dihalo-4-nitrophenol	*Cupriavidus* sp. CNP-8	2-dioxygenase	*6-Quinolinol*
2-nitro-benzoic acid	*P. fluorescens* KU-7	NR	*3-hydroxyanthranilic acid*
3-nitro-benzoic acid	*Pseudomonas* sp. JS51 *Comamonas* sp. JS46	ADO, 2-aminoethanethiol dioxygenase;	3,4-Dihydroxybenzoic acid
4-nitro-benzoic acid	*C. acidovorans*NBA-10 *Pseudomonas* sp. 4NT *Pseudomonas putida* TW3 *Ralstonia* sp. SJ98	NR	3,4-Dihydroxybenzoic acid
2C4NP	*Acinetobacter* sp.RKJ12	(MMO)	pyrocatechol

2-4-DNP (Dinitrophenol), 4C2NP (4-Chloro-2-nitrophenol), 2C5NP (2-Chloro-5-nitrophenol), NR (Nitroreductases), 4-Chloro 2-Amino Phenol (4-CAP).

Furthermore, there is ongoing exploration into enhancing the quality of lipids in cyanobacteria through feedstock engineering and genetic modification techniques, with a specific focus on reducing aromatic hydrocarbon levels [143]. This endeavor is driven by the goal of aligning cyanobacteria-derived biodiesel with the stringent requirements of contemporary combustion engines and environmental mandates. The endeavor to decrease aromatic hydrocarbons in cyanobacteria-derived biodiesel is not only a technical pursuit but also a crucial element in promoting sustainable and cleaner energy alternatives [123]. By integrating advancements in strain selection, cultivation optimization, transesterification processes, and post-production purification methods, researchers and engineers are striving to produce biodiesel of superior quality that not only meets industry standards but also contributes to a more eco-friendly energy landscape [144]. These evolving strategies highlight a dedicated effort to tackle the challenges associated with aromatic hydrocarbons and advance the feasibility of cyanobacteria-derived biodiesel within the broader framework of renewable energy solutions [145].

4.4. Combustion Potential and Sustainability

The combustion potential and sustainability of biodiesel produced from cyanobacteria are critical aspects that determine its viability as a renewable energy source [123]. Understanding the combustion characteristics and evaluating the overall sustainability of cyanobacterial biodiesel involves a comprehensive analysis of its chemical composition, combustion efficiency, and environmental impact [146]. Cyanobacteria-derived biodiesel exhibits favorable combustion properties owing to its composition of fatty acid methyl esters (FAMEs), primarily triacylglycerols (TAGs). The absence of sulfur, lower levels of aromatics, and higher cetane numbers contribute to improved combustion efficiency and reduced emissions compared to traditional fossil fuels [147]. The higher cetane number signifies better ignition quality, leading to smoother combustion and lower emissions of nitrogen oxides (NOx). The sustainability of cyanobacterial biodiesel extends beyond combustion efficiency to encompass environmental and social aspects [148]. Cyanobacteria offer advantages in terms of feedstock cultivation, as they can thrive in diverse environments, including non-arable land and wastewater. This reduces competition with food crops for resources, mitigating potential land-use conflicts associated with traditional biofuel feedstocks [149]. Moreover, cyanobacteria have the ability to sequester carbon dioxide during their growth, contributing to a closed carbon cycle when used as biodiesel feedstock. This carbon-neutral aspect aligns with the broader goal of mitigating greenhouse gas emissions and addressing climate change [150,151]. The potential integration of cyanobacterial cultivation in wastewater treatment processes further enhances the sustainability profile, providing a dual benefit of biofuel production and environmental remediation. To evaluate the combustion potential and sustainability comprehensively, life cycle assessments (LCAs) are employed [151,152]. LCAs consider the entire life cycle of biodiesel production, from cultivation and processing to distribution and combustion. Assessing factors such as energy input, greenhouse gas emissions, and resource use provides a holistic view of the environmental impact and sustainability of cyanobacterial biodiesel [153].

While cyanobacterial biodiesel demonstrates promising combustion potential and sustainability, ongoing research continues to refine cultivation techniques, optimize processing methods, and address challenges associated with scale-up. Integration with other biotechnological processes, such as nutrient recycling and co-cultivation strategies, further enhances the overall sustainability of cyanobacterial biodiesel production [154,155]. In conclusion, cyanobacteria-derived biodiesel exhibits favorable combustion characteristics, including higher cetane numbers and reduced emissions, making it a promising renewable energy option [147]. Its sustainability is underscored by its ability to thrive in diverse environments, carbon-neutral growth, and potential for environmental remediation. Cyanobacteria have shown success in environmental remediation, particularly in oil spill bioremediation, heavy metal removal, pesticide degradation, and wastewater treatment. Species such as *Oscillatoria salina* and *Synechococcus* sp. have been effectively used to clean up oil spills in aquatic environments. In wastewater treatment, cyanobacteria efficiently convert nutrients from dairy wastewater into biomass. While their potential for biofuel production is recognized due to their photosynthetic nature, most applications in this area are still in the research and development stage, focusing on improving efficiency and economic viability [156]. As the field advances, the continuous improvement of cultivation practices and processing methods ensures that cyanobacterial biodiesel remains a key player in the pursuit of sustainable and environmentally friendly energy alternatives [157].

5. Polyhydroxyalkanoates (PHAs) Production by Cyanobacteria

Polyhydroxyalkanoate (PHA) production by cyanobacteria represents a promising avenue within the field of bioplastics, offering a sustainable and environmentally friendly alternative to conventional plastics derived from fossil fuels [158]. The synthesis pathways for polyhydroxyalkanoates (PHAs) are real and well-established. Bacteria and archaea are the organisms that carry out the reactions to synthesize PHAs. As shown in Figure 3, there are at least 6 possible ways to synthesize PHAs from lignin depolymerization and

degradation into intermediates. (1) Pyruvate is converted to propionyl-coA by lactose dehydrogenase (LDH) and propionyl-CoA transferase (PCT) [159], and then PHAs is synthesized by PHA synthetase (PhaC). (2) Conversion from SucD, 4-hydroxy-butyrate dehydrogenase (4 hbD), 4-hydroxy-butyrate CoA transferase (Cat 1, Cat 2) to 4-hydroxy-butyrate coA, Then, PHAs are synthesized by PHA synthase (PhaC) [160]. (3) Succinic acid CoA is catalyzed by methylmalonyl-CoA decarboxylase (YgfG) and keto reductase (phaB) to form hydroxyvaleryl CoA, and finally to synthesize PHAs [161]. (4) Oxaloacetic acid was catalyzed by threonine dehydrogenase (IIVA), propionic acid dehydrogenase (LDH), ketoacylthiolase (BktB), ketoreductase (phaB), and PHA synthetase to synthesize PHAs. (5) Acetyl coenzyme A is catalyzed to synthesize PHAs by ketoacylthiolysis (phaA), ketoreductase (phaB) and PHA synthetase [3]. (6) de novo synthesis pathway of fatty acids, first acetyl-CoA is converted to malonyl ACP, Then PHAs [162,163] are synthesized under the pressure of FabG, 3-hydroxyl ester-ACP-CoA transferase (phaG), ACyl CoA transferase (Alkk) and PHA synthase. PHAs are biopolymers synthesized by various microorganisms as a means of carbon storage, and cyanobacteria, being photosynthetic organisms, are particularly well-suited for this purpose. As shown in (Figure 3), lignin depolymerizes and degrades into intermediates to synthesize PHAs. Cyanobacteria can accumulate PHAs intracellularly, especially when subjected to conditions of nutrient limitation, such as nitrogen or phosphorus deprivation [164,165]. These stress conditions trigger the diversion of excess carbon fixed through photosynthesis into the production of PHAs, serving as carbon and energy storage compounds. This natural ability of cyanobacteria to synthesize PHAs makes them attractive candidates for the sustainable production of biodegradable plastics [16]. Researchers are actively engaged in optimizing cultivation conditions to enhance PHA production in cyanobacteria. This involves manipulating various factors such as light intensity, carbon dioxide availability, and nutrient levels to achieve optimal conditions for both biomass growth and PHA accumulation [166]. Additionally, genetic engineering approaches are employed to enhance the efficiency of PHAs biosynthesis in cyanobacterial strains, enabling the development of engineered strains with improved PHA production capabilities [167]. The bioplastic potential of PHAs produced by cyanobacteria lies not only in their biodegradability but also in their versatility. PHAs can be engineered to exhibit specific material properties suitable for various applications, ranging from packaging materials to medical devices [168]. The sustainable and renewable nature of cyanobacteria as the source of PHAs aligns with the growing global emphasis on reducing dependence on fossil fuels and mitigating the environmental impact of plastic waste [169]. The production of PHAs by cyanobacteria also presents an opportunity for the integration of bioplastic synthesis with other biotechnological processes. For instance, the utilization of wastewater or carbon dioxide from industrial emissions as nutrient sources for cyanobacterial cultivation enhances the overall sustainability of PHA production [170]. This approach not only addresses environmental concerns but also contributes to the circular economy by utilizing waste streams for valuable bioplastic production [171].

In summary, the synthesis of polyhydroxyalkanoates (PHAs) by cyanobacteria signifies a forefront and eco-conscious strategy toward achieving sustainable bioplastic production. The adeptness of cyanobacteria in photosynthesis, coupled with continual innovations in genetic manipulation methodologies, establishes them as pivotal entities in the advancement of PHAs for an eco-friendlier and more cyclical paradigm in plastics manufacturing. As research progresses, the potential of polyhydroxyalkanoates (PHAs) sourced from cyanobacteria to significantly impact the bioplastics industry is burgeoning, offering a promising solution to the challenges posed by conventional plastics.

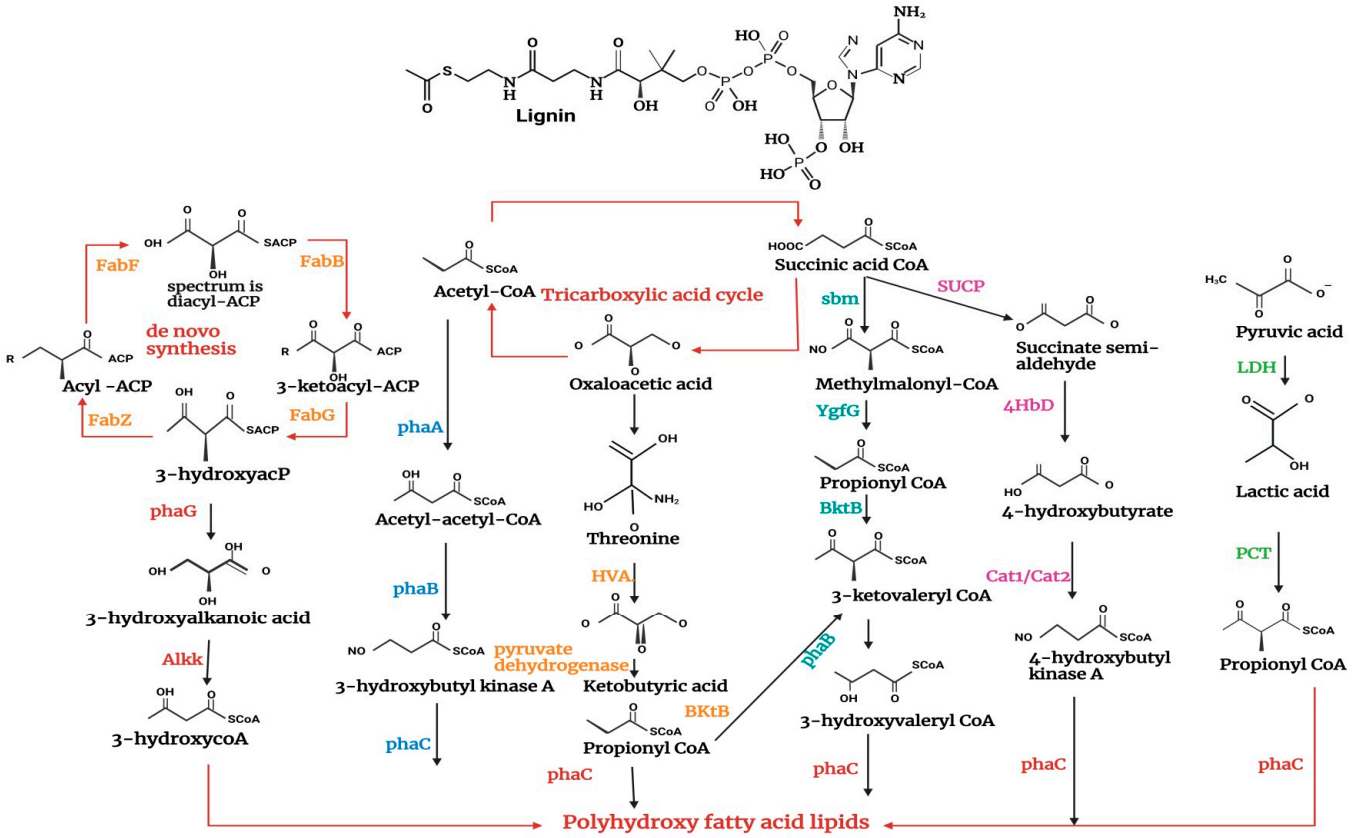

Figure 3. Innovative synthesis pathways for polyhydroxyalkanoates.

5.1. Intracellular Energy Source and Carbon Sink

The fundamental physiological and ecological importance of cyanobacteria stems from their dual roles as intracellular energy generators and carbon sequesters. As photosynthetic organisms, cyanobacteria harness solar energy to transform carbon dioxide into organic molecules via the photosynthesis pathway [36,109]. This process not only serves as an energy source for the cells but also functions as a carbon sink, contributing to carbon sequestration and ecosystem dynamics [172]. The primary intracellular energy source for cyanobacteria is derived from photosynthesis, a complex biochemical process that involves the capture of sunlight by photosynthetic pigments, such as chlorophyll-a, phycocyanin, and phycoerythrin [173]. These pigments are embedded in the thylakoid membranes, where light-dependent reactions take place. [174]. This process generates carbohydrates, such as glucose, as an energy storage reservoir for the cyanobacterial cells. Simultaneously, cyanobacteria act as carbon sinks by fixing atmospheric carbon dioxide into organic compounds during photosynthesis [175]. Photosynthetic bacteria can decompose propionic acid and butyric acid into acetic acid through their own extracellular secretion of an extracellular protease under phototrophic conditions, and then use CO_2 as an electron donor in the Calvin cycle to balance the redox potential of the cell, while acetic acid enters the tricarboxylic acid cycle (TCA) through the combined action of succinyl coenzyme A and glycine to synthesize ALA, the conversion pathway is shown in (Figure 4). This dual role as an energy source and carbon sink underscores their importance in global carbon cycling [55]. The incorporation of carbon into cellular biomass not only provides the necessary building blocks for the cell's growth and metabolism but also contributes to the reduction of atmospheric carbon dioxide, playing a crucial role in mitigating greenhouse gas levels [176]. Furthermore, cyanobacteria exhibit the ability to store excess carbon in the form of glycogen or polyhydroxyalkanoates (PHAs) under certain conditions [168]. These intracellular reserves serve as energy and carbon storage pools that cyanobacteria can tap into during periods of environmental stress or nutrient limitation [177]. The stor-

age and subsequent utilization of these reserves enhance the resilience of cyanobacteria in fluctuating environmental conditions, allowing them to thrive in various ecosystems, from freshwater to extreme environments such as deserts [56]. The comprehension of the complex equilibrium between serving as an internal provider of energy and a reservoir for carbon elucidates the adaptive tactics employed by cyanobacteria across various ecological habitats [67]. Additionally, the ability of cyanobacteria to sequester carbon holds significant ramifications for environmental sustainability, impacting the cycling of nutrients, the productivity of ecosystems, and the global carbon balance [46]. As scientists investigate the underlying molecular mechanisms dictating these phenomena, the distinctive function of cyanobacteria as pivotal agents in both energy fluxes and carbon modulation remains a compelling focus for researchers exploring the confluence of microbiology and environmental science.

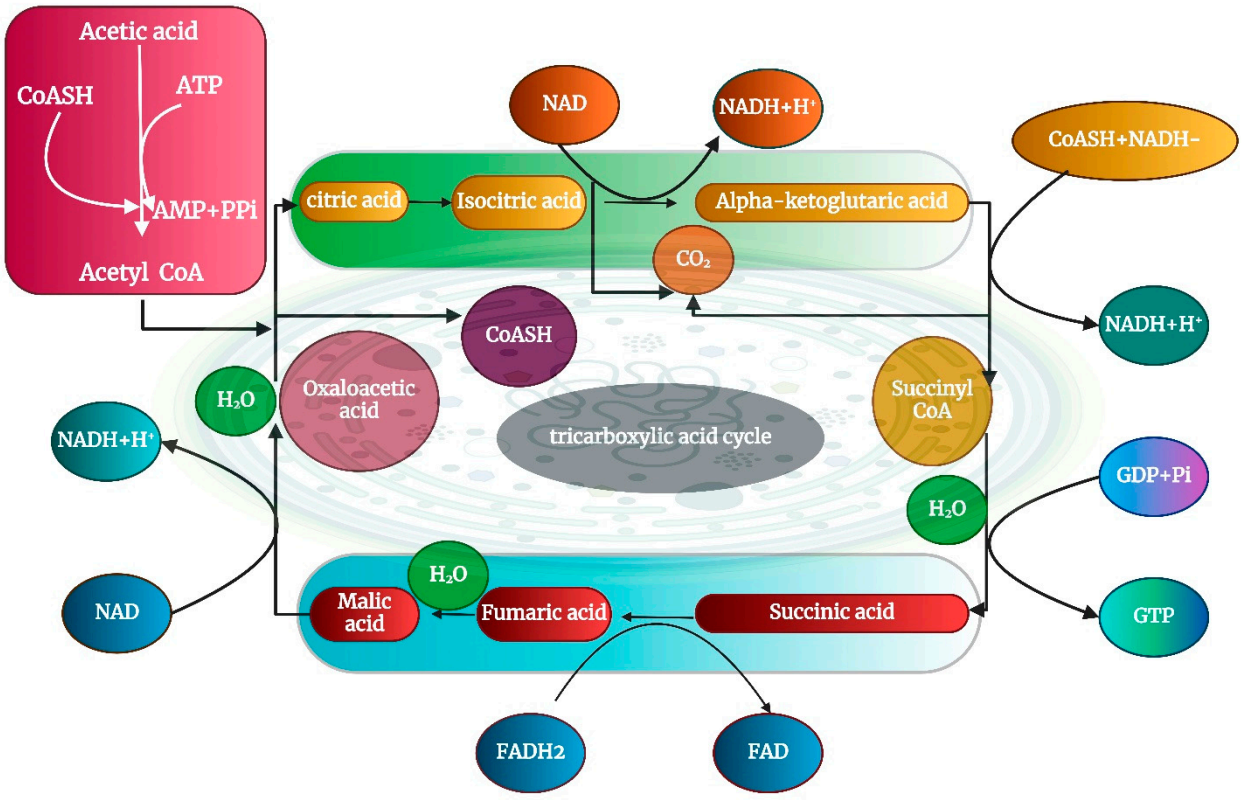

Figure 4. Photosynthetic cyanobacteria transformation and energy harvesting for ALA synthesis.

5.2. Cyanobacteria's Role in Bioplastic Production

Cyanobacteria play a significant and burgeoning role in the production of bioplastics, particularly through the synthesis of polyhydroxyalkanoates (PHAs). PHAs are biodegradable polyesters produced by various microorganisms as intracellular carbon and energy storage compounds [178]. Cyanobacteria, being photosynthetic organisms, offer a sustainable and environmentally friendly approach to bioplastic production [16]. The production of PHAs by cyanobacteria involves manipulating their metabolic pathways to divert carbon flux toward the synthesis of these biopolymers [179]. Under conditions of nutrient limitation, especially when deprived of nitrogen or phosphorus, cyanobacteria channel excess carbon, derived from photosynthesis, into the production of PHAs [180]. This serves as a natural strategy for these microorganisms to store carbon and energy for future use. Researchers are actively exploring the optimization of cultivation conditions and the genetic engineering of cyanobacterial strains to enhance PHA production [181]. Through precise adjustments of growth parameters such as light intensity, carbon dioxide concentration, and nutrient composition, researchers endeavor to establish an optimal milieu promoting both

biomass proliferation and the synthesis of polyhydroxyalkanoates (PHAs) within cyanobacterial cellular structures [182]. Additionally, genetic manipulation allows the development of cyanobacterial strains with improved PHA biosynthesis capabilities, offering potential for increased bioplastic yields. The bioplastic potential of cyanobacterial PHAs lies not only in their biodegradability but also in their versatility [183]. PHAs can be engineered to exhibit specific material properties suitable for various applications, including packaging materials, agricultural films, and medical devices [184]. The sustainable and renewable nature of cyanobacteria as the source of PHAs aligns with the global imperative to reduce reliance on fossil fuels and address the environmental challenges posed by conventional plastics [185].

Moreover, cyanobacteria play a pivotal role in enhancing the sustainability of bioplastic manufacturing owing to their adaptability to various environments, including non-arable land and wastewater, thereby mitigating the competition with food crops for resources [186]. Progress in cyanobacterial bioplastic production involves ongoing investigations into refining cultivation methods, improving processing techniques, and overcoming scalability challenges, alongside integration with complementary biotechnological processes such as nutrient recycling and co-cultivation strategies to bolster overall sustainability [187]. Additionally, the prospect of utilizing carbon dioxide emissions from industrial sources as a nutrient for cyanobacteria offers an added environmental advantage to the bioplastic production paradigm [16]. In summary, cyanobacteria, leveraging their intrinsic capacity for polyhydroxyalkanoate (PHA) synthesis, emerge as promising candidates for sustainable bioplastic manufacturing, underscored by interdisciplinary endeavors aimed at optimizing cyanobacterial strains, cultivation parameters, and downstream processing protocols [170,180].

5.3. Comparative Analysis with Conventional Plastics

The comparative analysis between bioplastics derived from cyanobacteria, specifically polyhydroxyalkanoates (PHAs), and conventional plastics reveals nuanced environmental considerations [188]. PHAs, synthesized by cyanobacteria through photosynthesis, not only demonstrate inherent biodegradability but also contribute to a closed carbon cycle, making them environmentally advantageous [189]. In contrast, conventional plastics, originating from petrochemicals, pose challenges related to non-biodegradability, leading to persistent waste accumulation and environmental harm [190]. The renewable source of cyanobacterial bioplastics is a key differentiator [191]. Cyanobacteria utilize sunlight and carbon dioxide to produce PHAs, presenting a sustainable alternative to conventional plastics that rely on finite fossil fuel resources [16]. The transition towards renewable feedstocks reflects a global imperative to mitigate carbon emissions and embrace sustainability [192]. In this context, the carbon neutrality achieved in Polyhydroxyalkanoates (PHAs) production offers significant environmental benefits [193]. Through photosynthesis, cyanobacteria effectively sequester carbon dioxide, contributing to atmospheric carbon reduction, unlike the carbon-intensive processes involved in conventional plastic production from fossil fuels [194]. By diminishing reliance on non-renewable resources, particularly prevalent in the petrochemical industry, cyanobacterial feedstocks present a viable pathway toward eco-friendly plastic manufacturing [16]. Moreover, the energy dynamics favor cyanobacterial bioplastics, with solar-powered photosynthesis offsetting downstream processing energy requirements, unlike the energy-intensive processes in conventional plastic production [195]. Waste management implications further underscore the superiority of cyanobacterial bioplastics, as their biodegradability lessens the strain on waste disposal systems compared to the persistence of non-biodegradable plastics [196]. In essence, the comprehensive analysis highlights the manifold environmental advantages of cyanobacterial bioplastics, especially PHAs, signaling a promising shift towards sustainable alternatives to conventional plastics [197].

5.4. PHAs as Parallel Competitors to Petrochemical-Based Plastics

Polyhydroxyalkanoates (PHAs) have emerged as potent contenders against petrochemical -based plastics, presenting a sustainable and eco-friendly option within the dynamic realm of plastic manufacturing [198]. PHAs, synthesized by cyanobacteria through the process of photosynthesis, offer a promising resolution to the environmental quandaries associated with traditional plastics derived from fossil fuels [199]. As concurrent rivals, various pivotal factors underscore the potential of PHAs to transform the plastics sector. One paramount advantage of PHAs is their inherent biodegradability, which sharply contrasts with the enduring nature of petrochemical-based plastics [200]. PHAs possess the ability to naturally degrade, thereby mitigating the environmental impact of plastic waste [201]. This attribute positions them as a compelling alternative amidst mounting apprehensions regarding plastic pollution and its detrimental repercussions on ecosystems [202].

Moreover, the renewable and carbon-neutral characteristics of PHA production further solidify their status as adversaries to petrochemical-based plastics [203]. The utilization of cyanobacteria, which harness solar energy and carbon dioxide during photosynthesis, contributes to a closed carbon cycle [204]. This presents a stark contrast to the carbon emissions stemming from the extraction and processing of fossil fuels for conventional plastics, aligning with global endeavors to combat climate change and transition towards sustainable practices [205]. A critical aspect of the competition between PHAs and petrochemical-based plastics lies in diminishing reliance on finite fossil fuels. By employing renewable resources for PHA production, the dependence on non-renewable fossil fuel sources is reduced, thereby addressing concerns related to resource depletion and environmental impact [206,207].

This shift is in harmony with the broader transition towards a circular economy and sustainable resource management practices. Energy consumption considerations further bolster the competitiveness of PHAs [208]. Although energy is requisite for downstream processing, the utilization of solar energy during photosynthesis diminishes the overall environmental footprint of PHA production [209]. In contrast, the energy-intensive procedures involved in fossil fuel extraction and refinement for conventional plastics contribute substantially to environmental strain. The versatility of PHAs concerning material properties further augments their competitiveness. PHAs can be tailored to exhibit specific characteristics suitable for a myriad of applications, ranging from packaging materials to medical devices. This adaptability positions them as feasible alternatives to petrochemical-based plastics across various industries, thereby offering a wide array of eco-conscious solutions [210–212].

In the final analysis, PHAs emerge as parallel contenders to petrochemical-based plastics, presenting a sustainable and environmentally mindful substitute. The biodegradability, renewability, carbon neutrality, and versatility of PHAs form a compelling rationale for their role in reshaping the future of plastic production, thereby fostering a more sustainable and circular economy. As research and technology progress, the rivalry between PHAs and conventional plastics is poised to drive innovation and promote a more environmentally responsible approach to plastic utilization and disposal.

6. Environmental Benefits of Cyanobacteria

Cyanobacteria, or blue-green algae, are pivotal agents in environmental sustainability due to their diverse biological activities, profoundly impacting ecosystems [213]. Primarily, they undertake photosynthesis, utilizing sunlight to convert carbon dioxide into organic compounds while liberating oxygen [214]. This photosynthetic process is indispensable for regulating atmospheric oxygen levels, supporting aquatic organisms' respiratory requirements, and enhancing overall air quality [215]. Moreover, cyanobacteria significantly contribute to carbon sequestration by assimilating atmospheric carbon dioxide during photosynthesis. This aids in mitigating greenhouse gas emissions, as carbon is integrated into their biomass, thereby reducing atmospheric carbon dioxide concentrations [216]. Certain cyanobacterial species exhibit the remarkable capability of fixing atmospheric nitrogen,

converting it into bioavailable forms for other organisms [217]. Indigenous bacteria capable of degrading MICROCYSTINs were found in the study. The isolated and screened strains included Proteobacteria, firmicutes, actinomyces, and fungi, and different strains showed differences in MICROCYSTIN degradation (Table 3). Some of these strains can simultaneously control algae and remove MICROCYSTINs [218]. Nitrogen fixation plays a crucial role in nutrient cycling within ecosystems, particularly in nitrogen-deficient environments, and fosters the growth of diverse plant species [219]. Additionally, cyanobacteria play a vital role in soil stabilization, especially in arid and semi-arid regions, by forming crusts that bind soil particles, preventing erosion, and enhancing soil structure [220].

In wastewater treatment, cyanobacteria are utilized for nutrient removal, efficiently absorbing and assimilating nitrogen, and phosphorus compounds from wastewater. This application aids in mitigating nutrient pollution in aquatic environments [221]. Furthermore, ongoing research explores the potential of cyanobacteria in biofuel and bioplastic production. Their capacity to convert sunlight and carbon dioxide into biomass offers a sustainable source of biofuels, while genetic engineering facilitates the production of biodegradable bioplastics, presenting environmentally friendly alternatives to conventional fossil fuel-derived plastics [222].

Cyanobacteria also support biodiversity in aquatic ecosystems, serving as a primary food source for various organisms and contributing to the intricate balance of food webs. Their ability to form symbiotic relationships further emphasizes their ecological significance [56,223]. Overall, the multifaceted roles of cyanobacteria in oxygen production, carbon sequestration, nutrient cycling, soil stabilization, wastewater treatment, and sustainable biofuel and bioplastic production underscore their pivotal contribution to environmental health and sustainability [224]. As ongoing investigations elucidate the nuanced ecological functions of cyanobacteria, these microorganisms persist as fundamental constituents within the intricate fabric of ecosystems, highlighting the efficacy of nature-derived approaches in mitigating modern environmental adversities.

Table 3. Exploring microcystin-degrading strains and their characteristics.

Strain Classification	Functional Strains	Target Microcystins	Initial Microcystins Concentration	Microcystins Degradation Efficiency	References
Bacillota	*Bacillus subtilis* (*strain 168*)	Microcystin-LR	6 μg/mL	(48 h)	[225]
Bacillota	*Bacillus brevis LEw-1238*	Microcystin-LR	6 μg/mL	(48 h)	[226]
Bacillota	*Bacillus thuringiensis LEw-2010*	MICROCYSTIN-RR	20 μg/mL	73% (3 d)	[226]
Bacillota	*Lysinibacillus boronitolerans strain CQ5*	Microcystin-LR	14.10 μg/L	90% (24 h)	[227]
Actinomyces	*Rhodococcus cavernicola C1-24*	Microcystin-LR	10 mg/L	9, 10, 8, 6, days	[228]
Actinomyces	*Brevibacterium F3*	MICROCYSTIN-RR	10 mg/L	9, 10, 7, 9, days	[228]
Actinomyces	*Arthrobacter* sp. *C6*	Microcystin-LR	10 mg/L	9, 10, 8, 5 days	[228]
Actinomyces	*Arthrobacter* sp. *F7*	MICROCYSTIN-LF	10 mg/L	9, 10, 7, 6, days	[228]
Actinomyces	*Arthrobacter sanguinis* sp. F10	Microcystin-LR	6 μg/mL	98% (4 days)	[229]
Actinomycetes	*Arthrobacter* sp. *strain R1*	Microcystin-LR	6 μg/mL	(4 days)	[229]
Actinomyces	*Arthrobacter* sp. *strain R6.*	Microcystin-LR	6 μg/mL	(4 days)	[229]
Actinomycetes	*Arthrobacter* sp. *strain R9*	Microcystin-LR	6 μg/mL	(4 days)	[229]
Actinomyces	*Arthrobacter sanguinis* sp. 423	Microcystin-LR	4 μg/L	25.88% (10 days)	[230]
Actinomycetes	*Arthrobacter sanguinis* sp. 443	Microcystin-LR	4 μg/L	17.91% (10 days)	[230]
Actinomycetes	*Bifidobacterium BB-12*	Microcystin-LR	110μg/L	59.12% (3 days)	[231]
Actinomycetes	*Bifidobacterium longum* BB-*46*	Microcystin-LR	110 μg/L	48.0% (3 days)	[231]
Actinomycetes	*Bifidobacterium BB-420*	Microcystin-LR	110 μg/L	48.8% (3 days)	[231]
Fungus	*Trichaptum* abietinum *1302BG*	Microcystin-LR	0.07 mg/L	(12 h)	[232,233]
Fungus	*Schizophyllum commune strain IUM1114-SS01*	Microcystin-LR	20 mg/L	(2 days)	[234]

Table 3. *Cont.*

Strain Classification	Functional Strains	Target Microcystins	Initial Microcystins Concentration	Microcystins Degradation Efficiency	References
Fungus	*ascomycete strain Trichoderma*	MICROCYSTINs	2.9 mg/L	(4 days)	[67]
Fungus	*Winter mucus d. ursingii strain EH5*	Microcystin-LR	0.05 mg/L	39% (3 days)	[235]
Fungus	*Aureobasidium pullulans KKUY0701*	MICROCYSTINs	3 mg/L	58.8% (1 h)	[236]
Proteobacteria	*Sphingomonas Paucimobilis . CBA4*	MICROCYSTIN-RR	150 µg/L	(3 days)	[237]
Alphaproteobacteria	*Sphingomonas* sp. *ACM-3962*	MICROCYSTIN-RR	15 mg/L	2.7 mg/(L·h)	[238]
Proteobacteria	*Pseudomonas paucimobilis*	MICROCYSTIN-RR	3 mg/L	0.09, mg/(L·h)	[239,240]
Proteobacteria	*Novosphingobium* sp. NV-3	Microcystin-LR	30 mg/L 3)	0.39 mg/(L·h)	[241]
Proteobacteria	*Sphingomonas parapaucimobilis 7CY*	MICROCYSTIN-LW	8 mg/L	5 days	[242]
Proteobacteria	*Sphingomonas Y2*	Microcystin-LR	22 mg/L	0.26 mg/(L·h)	[243]
Proteobacteria	*Novosphingobium* sp. *KKU15*	Microcystin-LR	6 µg/mL	(4 days)	[244]
Proteobacteria	*Novosphingobium* sp. *ERW19*	Microcystin-LR,	0.2 mg/L	0.010 mg/(L·h)	[245]
Proteobacteria	*Novosphingobium* sp. *ERN07*	MICROCYSTIN-RR	0.2 mg/L	0.007 mg/(L·h)	[245]
Proteobacteria	*Novosphingobium* sp. *KKU25s*	Microcystin-LR	30 µg/L	1.07 µg/(L·h)	[246]
Alphaproteobacteria	*Sphingopyxis* sp. a7	Microcystin-LR	14.5 mg/L	3.44 mg/(L·h)	[121]
Alphaproteobacteria	*Sphingopyxis* sp. *X20*	Microcystin-LR	7 mg/L	(2 days)	[122]
Alphaproteobacteria	*Sphingopyxis* sp. *YF1*	Microcystin-LR	15 µg/mL	53.6 µg/(mL·h)	[102]
Alphaproteobacteria	*Sphingopyxis* sp. USTB-05	MICROCYSTIN-LA	3.7 µg/L	(3 days)	[247]
Alphaproteobacteria	*Sphingosinicella microcystinivorans strain* B-9	MICROCYSTIN-RR	2.4 mg/L	0.06, mg/(L·h)	[239,240]
Alphaproteobacteria	*algicidal bacterium* Ochrobactrum sp. FDT5	Microcystin-LR	460.9 mg/L	(6 days)	[248]
Pseudomonadota	*R. solanacearum*	Microcystin-LR	9.6 mg/L	(2 days)	[249]
Pseudomonadota	*Bordetella* sp. *strain MC-LTH1*	MICROCYSTIN-RR	11, 8 mg/L	(3 days)	[250]
Beta Proteobacteria	*B pertussis.*	Microcystin-LR	18 µg/L	(2 days)	[251]
Pseudomonadota	*Methylobacillus* sp.	MICROCYSTIN-RR	3.7, 4.2 mg/L	<0.26, >0.26 mg/(L·h)	[252]
Pseudomonadota	*Paucibacter* sp. *KCTC 42545*	Microcystin-LR	11.8 µg/mL	(10 h)	[253]
Beta Proteobacteria	*Paucibacter toxinivorans* DSM 16,998;	MICROCYSTIN-LY	15 mg/L	8, days	[228]
Beta Proteobacteria	*Paucibacter toxinivorans* IM-4)	MICROCYSTIN-YR	0.95, mg/L	(3 days)	[119]
Pseudomonadota	*P. toxinivorans* (2C20 strain)	MICROCYSTIN-YR,	15, µg/mL	(8 days)	[254]
Pseudomonadota	*Comamonas*LEw-2	Microcystin-LR	10 µg/mL	(3 days)	[226]
Pseudomonadota	*Stenotrophomonas maltophilia . EMS*	Microcystin-LR	1.7 µg/mL	(2 days)	[255]
Pseudomonadota	*Stenotrophomonas maltophila* LEw-1278	Microcystin-LR	10 µg/mL	(2 days)	[226]
Pseudomonadota	*Stenotrophomonas maltophila*	Microcystin-LR	10 µg/mL	0.6 µg/(mL·h)	[256]
Gammaproteobacteria	*Xanthomonas beteli*	Microcystin-LR	39.4 mg/L	31, mg/(L·h)	[257]
Pseudomonadota	*Stenotrophomonas mori* sp.	MICROCYSTIN-LF	5.7 µg/mL	(12 days), (14 days), (15 days)	[258]
Pseudomonadota	*Morganella morganii*	Microcystin-LR	25 µg/L	3.77 mg/(L·h)	[259]
Pseudomonadota	*Pseudomonas aeruginosa UCBPP-PA14*	MICROCYSTIN-LW	350 µg/L 3)	85% (30 days)	[218]
Pseudomonadota	*Arthrobacter siderocapsulatus*	Microcystin-LR	350 µg/L 3)	37% (30 days)	[218]
Gammaproteobacteria	*Achromobacter xylosoxidans*	Microcystin-LR	150 µg/L	79.8% (7 days)	[260]
Gammaproteobacteria	*Enterobacter kobei*	Microcystin-LR	5 µg/mL	0.388 µg/(mL·h)	[261]
Bacillota	*Lacticaseibacillus rhamnosus*	Microcystin-LR	150 µg/L	(3 days)	[231]
Firmicutes	*Lacticaseibacillus rhamnosus Lc 705*	Microcystin-LR	150 µg/L	(3 days)	[231]
Bacillota	*Bacillus* sp.	MICROCYSTIN-RR	15 mg/L	(6 days)	[262]
Bacillota	*Bacillus subtilis*	MICROCYSTIN-RR	15 mg/L	(6 days)	[262]
Firmicutes	*B. thuringiensis* sp.	MICROCYSTIN-LR	20 mg/L	85% (10 days)	[263]
Bacillota	*Bacillus atrophaeus* sp.	MICROCYSTIN-RR	15 mg/L	(5 days)	[262]
Bacillota	*Bacillus* sp. *Ak3*	MICROCYSTIN-RR	25 µg/mL	75%(5 days)	[225]
Firmicutes	*Brevibacillus brevis LEw-1238*	MICROCYSTIN-LR	15 µg/mL	(3 days)	[226]

Table 3. *Cont.*

Strain Classification	Functional Strains	Target Microcystins	Initial Microcystins Concentration	Microcystins Degradation Efficiency	References
Bacillota	*Bacillus thuringiensis LEw-2010*	MICROCYSTIN-LR	15 μg/mL	(3 days)	[228]
Bacillota	*Lysinibacillus boronitolerans* (*T-10a*, *AB199591*)	MICROCYSTIN-LR	14.15 μg/L	(3 days)	[227]
Actinomycetota	*Rhodococcus cavernicola C1-24*	MICROCYSTIN-LR,	15 mg/L	5 days	[228]
Actinomycetota	*Brevibacterium F3*	MICROCYSTIN-LR,	15 mg/L	6 days	[228]
Actinomycetes	*Arthrobacter* sp. *C6*	MICROCYSTIN-LR	15 mg/L	5 days	[228]
	Arthrobacter sanguinis sp. F7	MICROCYSTIN-LR	15 mg/L	6 days	[228]
Actinomycetota		MICROCYSTIN-LY	10 mg/L	97 days	[228]
Corynebacterium	*Arthrobacter sanguinis* sp. F10	MICROCYSTIN-LR	7 μg/mL	(4 days)	[229]
Corynebacterium	*Arthrobacter sanguinis* sp. R1	MICROCYSTIN-LR	7 μg/mL	(4 days)	[229]
Bifidobacterium	*Arthrobacter sanguinis* sp. R6	MICROCYSTIN-LR	7 μg/mL	(4 days)	[229]
Actinomycetes	*Arthrobacter sanguinis* sp. R9	MICROCYSTIN-LR	7 μg/mL	(4 days)	[229]
Bifidobacterium	*Arthrobacter* sp. *423*	MICROCYSTIN-LR	55 μg/L	(10 days)	[230]
Actinomycetes	*Arthrobacter* sp. *JS443*	MICROCYSTIN-LR	5 μg/L	15.92% 10 days)	[230]
Bifidobacterium	*Bifidobacterium BB-12*	MICROCYSTIN-LR	150 μg/L	(2 days)	[231]
Bifidobacterium	*B. longum strains*	MICROCYSTIN-LR	150 μg/L	(2 days)	[231]
Bifidobacterium	*Bifidobacterium animalis subsp. lactis 420*	MICROCYSTIN-LR	150 μg/L	(2 days)	[231]

6.1. Carbon Sequestration and Reduction of Carbon Footprint

Cyanobacteria play a crucial role in the sequestration of carbon dioxide, actively participating in the reduction of carbon emissions and alleviating the consequences of human-induced carbon dioxide release [264]. Through the mechanism of photosynthesis, cyanobacteria utilize solar energy to convert carbon dioxide into organic molecules, facilitating the assimilation of carbon into their cellular structure [265]. This process of carbon fixation offers a twofold environmental benefit: it diminishes the concentration of atmospheric carbon dioxide, a significant greenhouse gas, while simultaneously providing a means for carbon retention within cyanobacterial cells [266]. By acting as a natural carbon sink, cyanobacteria contribute to the regulation of global carbon cycles, essential for mitigating the effects of climate change exacerbated by human activities such as fossil fuel combustion [267]. The efficiency of cyanobacteria in carbon sequestration underscores their significance in carbon offset endeavors and sustainable environmental strategies [268]. Moreover, ongoing research explores the potential of cyanobacteria for carbon capture and utilization technologies. By cultivating cyanobacteria in controlled settings such as photobioreactors and exposing them to carbon dioxide-rich industrial emissions, these microorganisms can absorb and convert emitted carbon dioxide into biomass [269,270]. This application not only aids in curbing greenhouse gas emissions but also holds promise to produce biofuels and other valuable bioproducts [271]. In the broader context of reducing carbon footprints, cyanobacteria demonstrate their potential as environmentally friendly agents of carbon sequestration and climate change mitigation [194]. Leveraging the innate carbon-fixing abilities of these microorganisms not only addresses environmental challenges but also emphasizes the importance of integrating nature-based solutions in the pursuit of sustainable, low-carbon pathways for the future [272]. As scientific inquiry progresses, the role of cyanobacteria in carbon sequestration emerges as a promising aspect of collective endeavors to combat climate change and minimize human-induced alterations to the global carbon equilibrium.

6.2. Sustainable Environmental Goals and Cyanobacteria's Contribution

Cyanobacteria significantly contribute to the attainment of sustainable environmental objectives, aligning with broader initiatives targeted at mitigating pressing challenges such as climate change, biodiversity loss, and environmental degradation [273]. Their

varied ecological functions and distinctive biochemical capabilities position cyanobacteria as valuable allies in the pursuit of sustainable environmental aims [274]. One notable contribution lies in carbon sequestration, as cyanobacteria actively participate in ameliorating climate change by sequestering atmospheric carbon dioxide during photosynthesis [194]. This directly aligns with global sustainability objectives aimed at reducing greenhouse gas emissions and achieving carbon neutrality. By assimilating carbon into their biomass, cyanobacteria serve as natural carbon sinks, playing a pivotal role in regulating atmospheric carbon levels and bolstering climate resilience efforts [275,276]. Cyanobacteria also play a crucial role in sustainable water management objectives, particularly in nutrient-rich environments [277]. Certain species exhibit nitrogen-fixing abilities, converting atmospheric nitrogen into accessible forms for other organisms [278]. This biological nitrogen fixation enhances nutrient cycling, fosters soil fertility, and bolsters the health of aquatic ecosystems. In wastewater treatment, cyanobacteria are utilized to eliminate surplus nutrients, addressing concerns associated with nutrient pollution and eutrophication [279]. Additionally, cyanobacteria contribute to sustainable agricultural practices by promoting soil stabilization [280]. In arid and semi-arid regions, cyanobacterial crusts aid in preventing soil erosion, maintaining soil structure, and fostering plant growth [281]. These ecological services play a vital role in promoting sustainable land use practices and combating desertification. The potential of cyanobacteria in biofuel and bioplastic production aligns with sustainable energy and resource management goals [282]. Through genetic manipulation and optimization of cultivation conditions, cyanobacteria can be engineered to produce biofuels, offering renewable alternatives to traditional fossil fuels [22]. Similarly, the production of biodegradable bioplastics from cyanobacteria addresses concerns related to plastic pollution and contributes to a circular economy approach [16]. In the context of the United Nations' Sustainable Development Goals (SDGs), cyanobacteria's multifaceted contributions align with several specific targets. These include SDG 13 (Climate Action) through carbon sequestration, SDG 6 (Clean Water and Sanitation) through nutrient cycling and water treatment, and SDG 15 (Life on Land) by promoting soil stability and biodiversity [68,283,284]. In summary, cyanobacteria emerge as crucial stakeholders in achieving sustainable environmental goals by addressing climate change, supporting nutrient cycling, contributing to water management, and providing alternatives in the production of biofuels and bioplastics. Their diverse ecological services underscore the importance of integrating cyanobacteria into comprehensive approaches for sustainable resource management and environmental conservation.

7. Efficiency of Cyanobacteria in Bioplastic Production

Cyanobacteria demonstrate remarkable efficiency in synthesizing bioplastics, particularly polyhydroxyalkanoates (PHAs), due to their inherent ability to conduct photosynthesis and possess unique metabolic pathways [285]. Their high photosynthetic efficiency enables the conversion of atmospheric carbon dioxide into biomass, serving as a sustainable carbon source for PHA synthesis [193]. When facing nutrient scarcity, cyanobacteria direct surplus carbon towards PHAs as intracellular reservoirs, highlighting their adeptness in carbon utilization. Genetic engineering advancements further enhance efficiency by enabling the customization of cyanobacterial strains to optimize PHAs production according to specific needs [16,286]. Various cultivation parameters such as light intensity, temperature, and nutrient availability significantly influence biomass and PHA yield. Strategic strain selection, considering both natural and engineered traits conducive to PHA production, also contributes to overall efficiency [287]. Effective downstream processing techniques for PHAs extraction and purification from cyanobacterial biomass are essential for bioplastic production efficiency [167]. Additionally, the utilization of renewable resources such as sunlight and carbon dioxide emphasizes the sustainability and environmental advantages of cyanobacteria-based bioplastics over conventional plastics [18]. Co-cultivation strategies leveraging symbiotic relationships and metabolic cooperation further enhance nutrient

utilization and biomass production efficiency, positioning cyanobacteria as promising contributors to sustainable and renewable bioplastics development as research progresses [288].

Plastic degradation is mainly completed by microorganisms. Some insect larvae eat plastic and their intestinal microorganisms play a role [289]. Fungi that degrade plastic are mainly filamentous fungi, whose hyphal structure is conducive to secreting extracellular enzymes and acting on plastics. In addition, fungi have multiple strategies to degrade different compounds, including powerful enzyme systems, strong adsorption capacity, and generation of biosurfactants [290]. Fungal hydrophobin plays an important role in the process of biological in-situ repair. Its double-layer structure can form an amphipathic film at the hydrophobic/hydrophilic interface. As a biosurfactant, it increases the contact area of the substrate, thereby increasing the contact area of the substrate. Greatly improve the degradation efficiency [290]. Bacteria lack similar structures, so it is generally believed that the degradation ability of fungi is generally higher than that of bacteria (Table 4).

Table 4. The remarkable plastic-degrading bacteria and fungi.

Plastic Type of (Bacteria)	Strain Species	Efficiency of Degradation	Time	Initiation of the Strain Top of Form	Refs.
Polyethylene	*Streptomyces* spp. *Streptomyces caatingaensis*" *Streptomyces cacaoi* *Streptomyces cadmiisoli* *Streptomyces caelestis* *Streptomyces caeni* *Streptomyces caeruleatus* *Streptomyces caespitosus*	27.5%	6 weeks	Nile Delta Lagoons	[291]
	Alcanivorax borkumensis	3.6% ± 0.36%	3 months	Seawater samples from northern Corsica (Gulf of Calvi, Mediterranean)	[292]
	Kocuria palustris M16	1% ± 0.063%	1 month	–	[293]
	P. aeruginosa, *P. fluorescens*, *P. putida*, *P cepacia*, *P stutzeri*, *P. maltophilia*, and *P putrefaciens.*	3.765%	2 months	Scrapyard in the north of Ibadan	[294]
	Bacillus sp. *B. cereus* *B. clausii* *B. polyfermenticus SCD* *B. pumilus*	16.7%	2 months	Waste Site in Incheon, South Korea	[295]
	Brevibacillus sp.	LDPE: 54.21% ± 7% HDPE: 46.4% ± 5%	4 months	An abandoned dump in Karnataka, India	[296]
	Bacillus anthracis	34.76% ± 4.04%	4 months	*Dandora Dumpsite landfill*	[297]
	Brevibacillus borstelensis strain B2, 2 (MG645267)	22.23% ± 2.20%	4 months	*Dandora Dumpsite landfill*	[297]
Polyvinyl chloride (*PVC*)	*Pseudomonas citronellolis*	18.56% ± 0.02%	1 month	–	[298]
	Erysipelothrix rhusiopathiae sp.	11.4% ± 0.6%	6 months	oceanic	[299]
	Bacillus sp. AIIW2	0.29%	3 months	oceanic	[300]
Polypropylene (pp)	*Stenotrophomonas panacihumi* PA3-2	20.9% ± 1.30% (molecular weight 10 300) 16.8% ± 1.70% (molecular weight 19 700)	3 months	Open-air solid wasteyard in South Korea	[301]
	Nocardia, *Rhodococcus*, *Amycolata*,. *Amycolatopsis*, *Gordona and Pseudoamycolata*	4.4% 6.5%	1 month	Sediment samples from mangroves in Matang, Peninsular Malaysia	[302]
	Bacillus and *Pseudomonas*	1.93% ± 0.18%	1 year	–	[303]
	Aneurinibacillus sp.	53% ± 2% (PP band) 46.2% ± 3% (PP board)	4 months	Wastewater Treatment Plant and Transfer Station Site	[296]
	Pseudomonas azotoformans, *P. stutzeri*, *Bacillus subtilis*, *B. flexus*	2.6%	1 year	Earth for dumping plastic waste	[304]

Table 4. *Cont.*

Plastic Type of (Bacteria)	Strain Species	Efficiency of Degradation	Time	Initiation of the Strain Top of Form	Refs.
Polystyrene (PS)	*Enterobacter* sp.,	15.4%	1 month	transfer station	[305]
	Pseudomonas sp., *Bacillus* sp.	25%	1 month	Exploring Soil Composition Near Plastic Waste Dump Site	[306]
	Pseudomonas aeruginosa	Bacillus subtilis exhibits the highest degradation efficiency. Top of Form	–	terrestrial sample	[307]
	Acinetobacter sp.	12.16%	2 months	*Tribolium castaneum* Intestine of a larva	[308]
	Pseudomonas aeruginosa	–	–	*Tribolium castaneum* Intestine of a larva	[309]
	Exiguobacterium sp. strain YT2	7.5% ± 0.5%	1 month	Larval intestine	[310]
	Pseudomonas aeruginosa strain DSM 50071	–	–	*Zophobas atratus*	[311]
polyurethane (*PUR/PU*)	*Bacillus subtilis* MZA-75,	Enhanced Degradation Potential through Co-cultivation	1 month	–	[312]
	Bacillus amyloliquefaciens	35–45%	4 weeks	–	[313]
Plastic type of (Fungi)	*Strain name*	Evaluation of Degradation Efficiency through Weight Loss Analysis	Incubation time	Origin of Microbial Strain	[314,315]
PE (HDPE) High-density polyethylene	*Aspergillus flavus PEDX3*	3.6125% ± 1.18%	1 month	Intestinal contents of the Galleria mellonella	[289]
	Penicillium oxalicum NS4 (*KU559906*)	20.18%	1 month	Plastic wasteyardnear Mohanpur campus	[316]
		48.53%	2 months		
		45.54%	3 months		
	Penicillium chrysogenum NS10 (*KU559907*)	14.05%	1 month	Plastic wasteyard near Mohanpur campus	[316]
		44.04%	2 months		
		56.548%	3 months		
Polyvinyl chloride (PVC)	*Chaetomium globosum* (*ATCC 16021*)	"Incipient PVC Absorption by Spores and Hyphae" Top of Form	1 month	Bought standard trunks	[317]
	Mucor rouxii	"Onset of Degradation in Glycerin and Urea Modified PVC" Top of Form	1 month	Polymer recycling site	[318]
	Phanerocheate chrysosporium	14%	1 month	Plastic waste landfill	[319]
PE (LDPE) Polyethylene	*Aspergillus oryzae strain A5, 1* (*MG779508*)	34.5% ± 4.55%	4 months	Dandola landfill soil	[297]
	Zalerion maritimum	57.4% ± 2.5%	14 days	–	[320]
	Rhizopus oryzae NS5	8.6% ± 4%	1 month	Laboratory isolate accession number KT160362	[321]
	Penicillium oxalicum NS4 (*KU559906*)	26.72%	1 month	Plastic wasteyard near Mohanpur campus	[316]
		28.70%	1 month		
		30.60%	3 months		
	Penicillium chrysogenum NS10 (*KU559907*)	30.32%	1 month	Plastic wasteyard near Mohanpur campus	[316]
		36.73%	2 months		
		44.36%	3 months		

Table 4. *Cont.*

Plastic Type of (Bacteria)	Strain Species	Efficiency of Degradation	Time	Initiation of the Strain Top of Form	Refs.
Polypropylene	*Phanerochaete chrysosporium*	5.5% (iPP/PLA/nCaCO$_3$ Nanocomposite)	1 month	Soil from the Indian campus	[319]
	Aspergillus niger	0.68% (PP)	1 month	–	
		2.40% (PP/PET/thermoplastic starch blend)	1 month		[322]
	Engyodontium album MTP091 (*F2*)	9.50% (UV pretreatment)	I year	Plastic trunk	[323]
	Lasiodiplodia theobromae	1.5%	3 months	Plant Endophytes inhabiting Psychotria flavida	[324]
PUR (*polyurethane*)	*Aspergillus tubingensis*	80%	60 days	Waste disposal site located in Islamabad, Pakistan.	[325]
	Chaetomium globosum	20–18%	3 months	–	[326]

7.1. Photosynthetic Process and Increased Production Efficiency

The photosynthetic mechanism in cyanobacteria is a fundamental determinant of their productivity and effectiveness across various applications, notably in augmenting the yield of valuable compounds such as biofuels and bioplastics [327]. Cyanobacteria, as photosynthetic prokaryotes, employ pigments such as chlorophyll-a, phycocyanin, and phycoerythrin for light absorption. This absorbed solar energy is subsequently transduced into chemical energy through intricate biochemical pathways [328]. Understanding the nuances of the photosynthetic process is critical for optimizing production efficiency. The process encompasses two primary phases: the light-dependent reactions and the light-independent reactions (Calvin cycle) [329,330]. During the light-dependent reactions within thylakoid membranes, solar energy drives the synthesis of ATP (adenosine triphosphate) and NADPH (reduced nicotinamide adenine dinucleotide phosphate) [174]. These high-energy molecules are indispensable for carbon dioxide fixation in the Calvin cycle, the light-independent reactions, occurring in the chloroplast stroma [331]. Maximizing photosynthetic efficiency in cyanobacteria involves modulation of several key parameters such as light intensity, wavelength, and duration. Cyanobacteria exhibit adaptive mechanisms to varying light conditions, adjusting their pigment composition and photosynthetic machinery for optimal light capture [332,333]. Researchers can manipulate these factors through environmental regulation during cultivation or genetic engineering to enhance overall photosynthetic efficiency. Genetic engineering facilitates the customization of cyanobacterial strains for heightened production efficiency by modifying crucial enzymes and pathways associated with photosynthesis, thereby redirecting carbon flux toward desired product synthesis [334,335]. Furthermore, enhancing cyanobacterial tolerance to environmental stressors, such as light and nutrient fluctuations, promotes sustained and efficient production [336]. Improvements in photosynthetic efficiency extend to the design of cultivation systems such as photobioreactors, offering controlled environments for optimizing light, temperature, and nutrient conditions to enhance productivity [337]. Advances in comprehending the molecular intricacies of cyanobacterial photosynthesis enable the development of strategies to enhance light absorption, energy transfer, and carbon assimilation [338]. In essence, the photosynthetic process in cyanobacteria serves as a pivotal conduit for converting solar energy into valuable biomass and bioproducts [339]. Enhancing the efficiency of this process necessitates a comprehensive approach integrating environmental management, genetic engineering, and innovative cultivation techniques [340]. As scientific exploration into the molecular underpinnings of cyanobacterial photosynthesis advances, the potential for heightened production efficiency and sustainable applications expands, driving progress in bio-based industries [36].

7.2. Limited Land Input and Acceptable Cost Implications

The utilization of cyanobacteria in diverse biotechnological endeavors, such as the production of biofuels and bioplastics, presents distinct advantages characterized by minimal land requirements and favorable cost implications [341]. These features render cyanobacteria particularly promising for sustainable production processes [342]. Their adaptability to cultivation in environments with limited land availability distinguishes them from traditional crops used for biofuel production, as they do not necessitate arable land or fertile soil [343]. Cyanobacteria exhibit robust growth capabilities in varied settings, including non-arable land and wastewater, thereby reducing competition with food crops for cultivation space and mitigating concerns regarding the land-use impact of biofuel and bioplastic feedstocks [344]. Additionally, the cost-effectiveness of cyanobacteria cultivation is notable, especially when contrasted with conventional biofuel feedstocks, owing to their low land input requirements [107]. The economic feasibility of cyanobacteria cultivation is particularly increased by the low land requirement compared to conventional biofuel raw materials. By introducing a multi-product approach, focusing on high-quality compounds, and using cost-effective cultivation methods, overall economics can be significantly improved. By integrating processes and optimization strategies, for example, through the use of agro-industrial waste and wastewater, input costs can be further reduced. Additionally, advances in nanotechnology and recycling strategies can increase production efficiency. These joint efforts make cyanobacteria a promising and cost-effective alternative for the sustainable production of biofuels and bioproducts [345]. Technological advancements in cultivation methods, such as the development of economical photobioreactor systems, contribute to the economic viability of cyanobacteria-based processes [346]. Cyanobacteria's efficient utilization of nutrients, including nitrogen and phosphorus, is pivotal for cost-effectiveness, reducing the necessity for excessive nutrient inputs [347]. Certain cyanobacteria species' ability to fix atmospheric nitrogen aids in sustainable nutrient cycling, aligning with environmentally conscious and economically sound practices [348]. Furthermore, the utilization of wastewater streams as a nutrient source serves a dual purpose of wastewater treatment and biomass production, diminishing the environmental impact of nutrient-rich wastewater while lowering cultivation costs. Leveraging unconventional nutrient sources enhances the overall cost-effectiveness of cyanobacteria-based processes [349,350]. In conclusion, cyanobacteria's minimal land requirements and favorable cost implications position them as promising candidates for sustainable biofuel and bioplastic production, in line with objectives aimed at minimizing environmental impact, mitigating resource competition, and advancing economically viable alternatives in the pursuit of a more sustainable and circular bio-based economy [158,351]. Continued research and technological innovations in cyanobacteria cultivation and bioprocess optimization further augment their potential for cost-effective and environmentally friendly applications in the bioenergy and bioplastics sectors.

7.3. Advantages over Other Sources of Bioplastics

Cyanobacteria present distinct advantages over alternative bioplastic sources, positioning them as promising contenders for sustainable and eco-friendly alternatives to conventional plastics. One notable advantage lies in their minimal land input demands [352]. Unlike certain bioplastic feedstocks derived from traditional crops, cyanobacteria do not necessitate arable land or fertile soil, thus mitigating concerns regarding land competition and fostering more sustainable bioplastic production. Another key advantage is their potential cost-effectiveness [353,354]. Cyanobacteria's rapid growth rates and scalability, particularly in controlled environments such as photobioreactors, contribute to high biomass productivity, enhancing the overall cost-effectiveness of cyanobacteria-based bioplastic processes [355]. Moreover, their ability to thrive in various environments, including non-arable land and wastewater, reduces reliance on costly nutrient supplementation, further bolstering economic viability [356]. The photosynthetic capability of cyanobacteria represents a significant advantage. Through photosynthesis, these microorganisms directly

convert solar energy into chemical energy, facilitating the synthesis of bioplastics from atmospheric carbon dioxide [16]. This renewable and carbon-neutral approach contrasts with certain bioplastic feedstocks reliant on agricultural inputs and processes contributing to a carbon footprint [357]. Cyanobacteria's photosynthetic efficiency aligns with the broader goal of reducing dependence on finite fossil fuels and mitigating climate change impacts associated with conventional plastics [100]. Additionally, their genetic adaptability serves as a platform for tailored bioplastic production. By employing genetic engineering, researchers can optimize cyanobacterial strains to enhance the synthesis of specific bioplastics with desired properties, allowing thproduction of customized bioplastics suited to diverse applications [285,358].

Furthermore, cyanobacteria demonstrate versatility in growth conditions, thriving in diverse climates from arid regions to aquatic environments, surpassing certain crop-based bioplastic feedstocks in adaptability [359]. This adaptability contributes to the resilience and reliability of cyanobacteria-based bioplastic production systems [360]. In close, the advantages of cyanobacteria, including their low land input requirements, cost-effectiveness, photosynthetic efficiency, genetic malleability, and versatile growth conditions, position them as compelling and sustainable candidates for eco-friendly alternatives to conventional plastics. They offer a pathway to address environmental concerns associated with plastic pollution and contribute to the development of a circular bio-based economy.

8. Achievements and Constraints in Commercialization Pathway

The advancement of cyanobacteria-based technologies along the commercialization pathway has yielded significant progress, particularly in the domains of bioplastic and biofuel synthesis [286]. Cyanobacteria, functioning as photosynthetic microorganisms, have exhibited their capability in generating polyhydroxyalkanoates (PHAs), a class of biodegradable bioplastics, thereby holding promise for mitigating the environmental impact of conventional plastics [180]. Moreover, within the realm of biofuels, cyanobacteria have demonstrated efficacy in harnessing sunlight and carbon dioxide to produce renewable energy sources, contributing to the pursuit of sustainable alternatives [361]. Notably, they have been effectively employed in wastewater treatment processes, efficiently absorbing and metabolizing nutrients from wastewater, thereby offering a dual advantage of nutrient removal and biomass production [362]. This utilization aligns with sustainable environmental practices and presents a practical solution to challenges in wastewater management [363]. Genetic engineering advancements have significantly augmented cyanobacteria's capacities for bioplastic and biofuel synthesis by optimizing metabolic pathways, resulting in enhanced yields and improved product characteristics [16]. These genetic engineering breakthroughs represent a significant step toward the commercial viability of cyanobacteria-based technologies [107]. However, despite these achievements, various constraints persist along this commercialization trajectory. Challenges such as elevated production costs, scalability limitations, and technological intricacies pose hurdles that necessitate careful consideration [364]. The refinement of cultivation systems, downstream processing techniques, and the resolution of scalability concerns are essential for bridging the gap between laboratory-scale successes and large-scale commercial applications [365]. Furthermore, ensuring regulatory compliance and garnering public acceptance are pivotal for the widespread adoption of cyanobacteria-based technologies [366]. While notable strides have been made in the commercialization of cyanobacteria-based technologies, addressing existing constraints is imperative for realizing their full potential [367]. Continued research, technological innovation, and strategic collaborations will be instrumental in overcoming these challenges and establishing cyanobacteria as viable contributors to sustainable bioplastic and biofuel production at a commercial scale.

Challenges Faced in Scaling up Cyanobacteria-Based Production

Expanding the production of bioplastics using cyanobacteria encounters a multitude of complex challenges that demand meticulous analysis and inventive solutions. Among

these challenges, cost-effectiveness stands out as paramount [368,369]. As production scales up, operational expenses inevitably increase, underscoring the need for economical cultivation methods, downstream processing, and extraction techniques to ensure the economic viability of large-scale cyanobacteria-based production [370]. Additionally, scalability presents a significant hurdle in transitioning from small laboratory experiments to industrial production [371]. Optimizing growth conditions, light distribution, and nutrient availability becomes increasingly intricate as production scales [372]. Overcoming these challenges necessitates innovative design approaches for photobioreactors and cultivation strategies capable of maintaining efficiency and consistency at larger scales [373].

Furthermore, addressing the nutrient requirements of cyanobacteria, essential for their growth, poses challenges in sourcing and sustainability when scaling up [374]. Ensuring a stable and sustainable nutrient supply, especially in open pond systems, is crucial and intersects with broader environmental sustainability concerns. Balancing productivity and product quality remains an ongoing challenge, requiring constant refinement of growth conditions, light exposure, and nutrient utilization to enhance overall efficiency and economic feasibility [375,376]. Navigating regulatory compliance is also critical as cyanobacteria-based technology progresses toward commercial deployment. Adhering to regulations pertaining to environmental safety, product quality, and overall compliance is vital for successful large-scale production. Establishing clear regulatory guidelines and fostering collaboration between industry stakeholders and regulatory bodies are imperative for creating a conducive environment for large-scale implementation [377–379]. Moreover, downstream processing complexities, particularly in extracting and purifying bioplastics from cyanobacterial biomass at industrial scales, present additional challenges. Developing scalable and cost-effective separation and purification technologies is essential for maintaining economic viability [380–382]. Public perception and acceptance further complicate matters, particularly regarding safety and environmental impact. Educating the public and providing transparent information are crucial for overcoming societal resistance to large-scale implementation. Addressing public concerns and engaging in outreach efforts are essential for building acceptance and support [383,384]. However, the technological complexity associated with scaling up cyanobacteria-based production introduces challenges in monitoring, control, and automation. Innovations in process engineering and control systems are necessary to ensure the robustness and reliability of large-scale cultivation [385]. Collaborative efforts involving researchers, industry stakeholders, and regulatory bodies are vital for overcoming these challenges, fostering innovation, and realizing the full potential of cyanobacteria-based production at a commercial scale [386,387].

9. Cyanobacterial Species as Sources of Green and Clean Energy

Cyanobacterial species are attracting significant scientific interest as potent candidates for sustainable energy sources, leveraging their distinct photosynthetic abilities and metabolic pathways [388]. A primary focus of the investigation revolves around the potential of cyanobacteria for biofuel production [389]. These microorganisms serve as inherent biofuel factories, utilizing sunlight and carbon dioxide for the direct synthesis of biofuels such as biodiesel and bioethanol [390]. Researchers are actively involved in refining cyanobacterial strains through genetic manipulation to enhance the production of lipids and carbohydrates, crucial constituents in biofuel synthesis. This approach not only presents a sustainable alternative to traditional fossil fuels but also holds promise for carbon-neutral energy production [22,391]. In the domain of hydrogen production, specific cyanobacterial species demonstrate the remarkable capability to generate molecular hydrogen via photobiological processes. Through harnessing solar energy, cyanobacteria facilitate the breakdown of water molecules, releasing hydrogen as a clean and renewable byproduct. This photobiological hydrogen production method shows significant potential as an environmentally friendly approach to addressing the rising demand for hydrogen fuel, thereby contributing to a more sustainable energy landscape [392–394].

Furthermore, cyanobacteria exhibit potential in electricity generation through microbial fuel cells (MFCs) [395]. Within these systems, cyanobacteria serve as biocatalysts, utilizing their photosynthetic activity to produce electrons from organic matter, which can then be utilized to generate electrical energy [396]. Although the efficiency of cyanobacteria in MFCs is an active area of investigation, the concept of employing cyanobacteria as green catalysts for electricity production presents an intriguing avenue for sustainable power generation [397]. Apart from energy production, cyanobacteria also play a vital role in carbon capture and storage [398]. Through photosynthesis, cyanobacteria capture carbon dioxide from the atmosphere, aiding in the mitigation of greenhouse gas emissions [399]. This dual functionality highlights the versatility of cyanobacteria, positioning them not only as energy producers but also as crucial contributors to efforts aimed at combating climate change [400]. However, despite the promising potential of cyanobacteria in green energy production, challenges persist. Optimizing growth conditions, enhancing productivity, and addressing scalability concerns are ongoing research priorities. The economic viability of large-scale cyanobacteria-based energy production necessitates careful consideration of factors such as cultivation systems, nutrient availability, and downstream processing [401–403].

In essence, cyanobacterial species embody adaptable and eco-friendly reservoirs of renewable energy. Ranging from biofuel synthesis to hydrogen generation and electrical power generation, the distinctive attributes of cyanobacteria present diverse strategies for addressing the worldwide energy dilemma. Persistent exploration and advancements in technology are imperative for maximizing the complete capacity of cyanobacteria-mediated energy generation, thereby fostering the development of a more environmentally friendly and sustainable energy landscape.

9.1. Diversity of Cyanobacterial Species

Cyanobacteria, a diverse assembly of photosynthetic prokaryotes, exhibit a wide array of morphological, physiological, and ecological traits [48]. These microorganisms demonstrate notable versatility in adapting to various environments, thriving in environments ranging from freshwater bodies to extreme habitats such as hot springs and polar regions [404]. Their morphological diversity encompasses unicellular, filamentous, and colonial forms, each characterized by distinct structures such as trichomes or mucilaginous sheaths [405]. Renowned for their vibrant pigmentation, cyanobacteria employ pigments such as chlorophyll-a, phycocyanin, and phycoerythrin, resulting in the characteristic blue-green hue, though certain species manifest a spectrum of colors [406]. Primarily relying on photosynthesis, cyanobacteria played a crucial role in the evolution of oxygenic photosynthesis, contributing significantly to the oxygenation of Earth's atmosphere [407]. Their metabolic repertoire extends to nitrogen fixation, facilitated by specialized cells such as heterocysts [408]. Ecologically, cyanobacteria contribute to primary production, nutrient cycling, and symbiotic relationships with plants, yet they can also form harmful algal blooms under specific conditions, generating toxins with potential ecological and health ramifications [409]. A thorough comprehension of cyanobacterial diversity is imperative for elucidating their ecological functions and potential applications across diverse ecosystems [410].

9.2. High Potential in Biofuel Production

Cyanobacteria demonstrate considerable promise for biofuel generation, offering a sustainable and renewable energy solution [123]. Capitalizing on their distinct photosynthetic prowess, these microorganisms efficiently convert sunlight and carbon dioxide into biofuels, presenting an eco-friendly alternative to conventional fossil fuels [411]. The primary focus centers on biodiesel and bioethanol production [412]. Through genetic engineering, cyanobacteria such as Synechocystis and Synechococcus have been modified to boost lipid and carbohydrate synthesis, essential precursors for biofuel production [413]. Lipids, especially, serve as valuable raw materials for biodiesel manufacture. Genetic

manipulation endeavors strive to enhance metabolic pathways within cyanobacteria, augmenting their efficacy in accumulating these biofuel precursor compounds [147]. One of the principal advantages of cyanobacteria in biofuel generation lies in their capacity to thrive in non-arable land and diverse environmental conditions [186]. This adaptability mitigates resource competition with food crops and diminishes the environmental impact associated with land-use alterations [414]. Moreover, cyanobacteria can be cultivated in enclosed systems such as photobioreactors, enabling precise regulation of growth parameters and heightened productivity [415]. Ongoing research endeavors continuously explore cyanobacteria's potential as a biofuel source by tackling challenges related to optimizing growth conditions, increasing biomass output, and refining downstream processing techniques for efficient biofuel retrieval [416]. Progress in synthetic biology and metabolic engineering is facilitating the development of tailored cyanobacterial strains with enhanced biofuel generation capabilities [417]. As these technologies advance, cyanobacteria are poised to play a crucial role in the transition toward sustainable and carbon-neutral biofuel production, significantly contributing to global efforts to mitigate climate change and secure a cleaner energy future [147,418].

9.3. Role in the Production of Biodegradable Plastics

Cyanobacteria are pivotal in the synthesis of biodegradable plastics, providing an ecologically sound substitute for conventional petroleum-derived plastics [419]. The utilization of cyanobacteria for this purpose is rooted in their innate capacity to produce polyhydroxyalkanoates (PHAs), a category of biopolymers suitable for biodegradable plastic production [420]. Through manipulation of their metabolic pathways, researchers have effectively engineered cyanobacterial strains to augment PHA synthesis [167]. Prominent cyanobacteria such as Synechocystis and Synechococcus have been subject to genetic modifications to enhance PHA production, showcasing the adaptability of these microorganisms in sustainable bioplastic manufacturing [16]. The advantage of employing cyanobacteria lies in their photosynthetic prowess, enabling them to harness solar energy and convert carbon dioxide into biomass rich in PHAs [421]. This process aligns with the ethos of a circular economy, utilizing renewable resources and diminishing reliance on fossil fuels [422]. Furthermore, cyanobacteria can be cultivated in diverse environments, including enclosed systems such as photobioreactors, affording control overgrowth parameters and facilitating scalable production of biodegradable plastics [423]. Endeavors are ongoing to optimize cyanobacteria-based bioplastic production by addressing variables such as strain selection, cultivation conditions, and nutrient availability [424]. Researchers are investigating methods to enhance the efficiency of PHA extraction and subsequent processing, ensuring an economically viable and environmentally sustainable bioplastic production pipeline [425]. With increasing demand for environmentally conscious alternatives to traditional plastics, cyanobacteria emerge as a promising solution for biodegradable plastics [16]. Their singular capacity to utilize sunlight and carbon dioxide for PHA synthesis situates cyanobacteria at the vanguard of sustainable bioplastic production, contributing to global efforts to mitigate the environmental ramifications of plastic waste [426,427]. Ongoing research and technological progress in this domain hold the potential to establish cyanobacteria as pivotal contributors to the advancement of biodegradable plastics, fostering a greener and more sustainable trajectory for the plastics industry.

10. Conclusions

In conclusion, cyanobacteria demonstrate a broad spectrum of metabolic functionalities, including but not limited to carbon fixation, biofuel synthesis, and biopolymer formation, thereby substantiating their crucial role in sustainable biotechnological pursuits. Advancements in genetic engineering and cultivation techniques are indispensable for maximizing the potential of cyanobacteria across these domains. In particular, directing cyanobacteria to synthesize polyhydroxyalkanoates (PHAs) for eco-friendly plastic production represents a groundbreaking tactic in line with circular economy principles. This strategy addresses

ecological apprehensions while endorsing efficient waste treatment. Subsequent research endeavors should focus on refining cyanobacterial strains via genetic interventions, exploring sophisticated systems biology methodologies, and enhancing sustainable cultivation protocols to fully exploit their potential to promote sustainability. Future research directions could include developing advanced genetic tools to improve cyanobacteria metabolic pathways to enable higher yields of biofuels and biopolymers utilizing systems biology approaches to understand and optimize the complex interactions within cyanobacterial cells and their environment, and innovative cultivation techniques that minimize resource use and maximize productivity, using wastewater for nutrient supply and integrating renewable energy sources conducting comprehensive studies on the environmental impacts of large-scale cyanobacterial applications to ensure ecological balance and sustainability; and exploring the economic viability and market potential of cyanobacteria-derived products to facilitate their transition from research to commercial use. Ultimately, cyanobacteria represent innovative ways to promote a greener and more resilient future and contribute significantly to global sustainability efforts by providing renewable energy sources, biodegradable materials, and efficient waste management solutions.

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