

Review Article

The Advancement of Microalgal Cultivation Technology: Current Trends and Future Prospectives

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Abstract

Microalgae have emerged as promising sustainable bioresources due to their rapid growth, metabolic versatility, and capacity to produce diverse valuable compounds, including biofuels, nutraceuticals, pigments, and bioplastics. This review focusses microalgal cultivation technologies, encompassing open systems, closed photobioreactors (tubular, flat-panel, bubble-column designs) and biofilm techniques. It contrasts each system's advantages and limitations in productivity, contamination control, energy efficiency, and scalability. Advances in strain improvement via genetic engineering and synthetic biology are examined alongside innovative cultivation strategies like co-cultivation and biofilm-based systems for enhancing biomass yield and sustainability. The integration of automation, real-time monitoring, and artificial intelligence for optimized cultivation management is dissected. Recent breakthroughs in reactor design, automation, real-time monitoring, and genetic engineering collectively boost process efficiency and scalability. Despite persistent hurdles in contamination control, nutrient supply, and energy-intensive harvesting, continuous innovation is accelerating microalgae's path toward commercial viability, cementing their central role in a sustainable, circular bioeconomy. The aim of this review is to provide a comprehensive synthesis of recent technological developments and innovative strategies in microalgal cultivation that enhance biomass productivity, sustainability, and economic viability.

Keywords

Microalgae, Photobioreactor, Genetic Engineering, Synthetic Biology, Co-Cultivation, Downstream Processing

1. Introduction

Microalgae are microscopic, predominantly unicellular photosynthetic organisms inhabiting freshwater and marine environments which are existing individually or colonially [1]. Unlike higher plants, they lack roots, stems, and leaves but possess chlorophyll and auxiliary pigments enabling photosynthesis [2]. Microalgal cultivation technology employs systems engineered to optimize mass biomass production [3]. *Open systems* like raceway ponds offer cost-effectiveness and

scalability but remain vulnerable to contamination and environmental swings. Conversely, *closed photobioreactors (PBRs)* including tubular, flat-panel, and bubble-column reactors provide superior control over light, temperature, and nutrients, boosting productivity while curbing contamination [4, 5]. Advances span biofilm-based systems, co-cultivation approaches, and integration with wastewater treatment/CO₂ sequestration to enhance sustainability and economics. Op-

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timizing parameters *light intensity/quality, pH, temperature, z nutrient matrix* proves critical for maximizing biomass yield and product quality [6]. Emerging technologies like automation, real-time monitoring, genetic engineering, and synthetic biology further amplify cultivation efficiency and scalability [7, 8].

Microalgae are pivotal in driving a sustainable bioeconomy and advancing biotechnology. Their rapid growth, high biomass productivity, and metabolic versatility enable them to produce diverse valuable products including food, feed, pharmaceuticals, biofuels, and biomaterials [9-12]. Environmentally, microalgae support sustainability by sequestering CO₂, treating wastewater, and reducing pollution, directly contributing to climate change mitigation and circular economy models [13]. Their cultivation demands minimal arable land, freshwater, and agrochemicals, offering an eco-friendly alternative to conventional agriculture and fossil-based industries [14].

When integrated into biorefineries, microalgae enable near-zero-waste systems by valorizing all biomass components. This enhances economic feasibility while reducing environmental footprints. Despite persistent challenges in scaling production and achieving cost-competitiveness, microalgae's versatility across sectors solidifies their role as essential drivers of a green, carbon-neutral, and resource-efficient bioeconomy [15].

Microalgae represent a fundamental pillar of sustainable biotechnology and the burgeoning bioeconomy due to their diverse and impactful applications across numerous sectors [16]. Their high lipid content and rapid growth rate position them as a highly promising renewable feedstock for producing biofuels like biodiesel, biomethane, hydrogen, and ethanol, offering a lower-emission alternative to conventional fossil fuels [17]. Furthermore, microalgae are nutritionally rich, packed with proteins, antioxidants, valuable pigments, and bioactive compounds, making them essential sources for nutraceuticals and functional food ingredients that deliver significant health benefits, including anti-inflammatory and antioxidant effects [18, 19]. The cosmetic industry also leverages microalgal extracts as natural sources of pigments, antioxidants, and moisturizing agents, enabling the development of more eco-friendly and sustainable product formulations [20, 21]. Beyond direct products, microalgae play a critical environmental role in wastewater treatment through phycoremediation, efficiently removing nutrients and contaminants while simultaneously generating usable biomass [22, 23]. Additionally, their capacity for photosynthetic carbon fixation makes them powerful agents for CO₂ sequestration, contributing significantly to carbon capture efforts; this process can be directly integrated with industrial flue gas treatment, mitigating greenhouse gas emissions and advancing carbon-neutral industrial processes [24]. Collectively, these multifaceted applications underscore the immense potential of microalgae to drive sustainable development and innovation within the energy, health, environmental man-

agement, and industrial sectors [25, 26].

Driven by the urgent need to overcome persistent productivity, cost, and scalability limitations, this review examines recent advances in microalgal cultivation, as resolving these challenges is fundamental to unlocking microalgae's full potential as a sustainable resource. Significant progress has been achieved through innovations like advanced photobioreactors, real-time biosensing, and IoT-driven automation, enhancing control over growth conditions and boosting biomass yields [27, 28]. However, critical hurdles remain formidable, including contamination risks, sustainable nutrient supply constraints, and the energy-intensive nature of harvesting processes [29-32]. Concurrently, emerging approaches, such as genetic engineering, synthetic biology, and co-cultivation systems are rapidly expanding the capabilities of microalgae for producing diverse high-value bioproducts and enabling novel environmental applications [33, 34]. Synthesizing these developments through a comprehensive review serves vital purposes: it identifies critical knowledge gaps, guides targeted future research efforts, and supports the development of scalable, economically viable microalgal production systems [15]. Such systems are indispensable for advancing crucial global goals in carbon mitigation, efficient wastewater treatment, and the realization of a circular bioeconomy [35, 36]. As microalgae technologies transition from laboratory research to commercial markets, sustained multidisciplinary innovation across biology, engineering, and policy remains essential to meet both pressing sustainability targets and the demands of the marketplace [37, 38].

2. Overview of Microalgal Cultivation System

Microalgal cultivation systems can be broadly classified into three main categories: open pond systems, closed systems (photobioreactors) and attachment or biofilm system, each with distinct characteristics, advantages, and limitations [4]. Microalgal cultivation systems are chosen based on trade-offs between cost, productivity, contamination risk, and scalability [39].

2.1. Open Pond System

Open cultivation systems notably raceway ponds and high-rate algal ponds (HRAPs) continue to dominate large-scale microalgae production owing to their compelling economics, low construction/operational costs, and inherent scalability [39, 40]. Raceway ponds, characterized by shallow oval channels (typically ~0.3 m deep), utilize paddlewheels to circulate cultures, preventing sedimentation and ensuring adequate mixing [41]. These systems are operationally simple, energy-efficient compared to closed photobioreactors, and remain the most viable option for industrial-scale deployment. However, significant limitations persist, including high contamination risks from invasive microorganisms (e.g., bacteria,

competing algae) and grazers (rotifers, amoebae); vulnerability to environmental exposure causing temperature fluctuations, evaporation losses, and rainfall dilution that disrupt salinity and pH; and inherently lower biomass productivity due to restricted light penetration and self-shading at elevated cell densities [42]. Despite these challenges, open raceway ponds remain the most cost-effective and scalable solution, particularly when cultivating robust algal strains adapted to extreme conditions that naturally resist contamination. Strategic optimization of pond depth (30-35 cm) and initial biomass concentration can enhance performance, yet fundamental technological advances remain critical to overcome persistent productivity ceilings and contamination vulnerabilities inherent to open systems [43, 39].

2.2. Closed System (Photobioreactor)

Photobioreactors (PBRs) are closed microalgal cultivation systems that encompass diverse designs like *tubular*, *flat-panel*, *bubble-column*, and *hybrid configurations*. Engineered for tighter control over light, temperature, pH, and nutrients, PBRs typically achieve higher biomass productivity and product quality than open systems [44, 45, 5]. Among these, *tubular PBRs* dominate industrial-scale applications. Their transparent tubes (arranged serpentine, helical, or vertically) maximize surface area-to-volume ratios, optimizing light exposure and gas exchange via airlift or pumped circulation [28]. While they minimize contamination and enable precise culture management, their capital and operational costs are substantial; investment estimates show ~ €0.51 million per hectare at 100-hectare scales [46].

Flat-panel PBRs use thin, vertical chambers to boost light capture and support efficient mixing/gas transfer [47]. Innovations like disposable plastic bags cut costs, while internal illumination enhances light distribution [5]. These systems excel in producing high-value pigments, though hydrodynamic stress and uneven light-cell interactions can limit growth. *Bubble-column and airlift PBRs* leverage simple designs with strong mixing and gas-liquid mass transfer [48, 49]. Studies confirm bubble columns outperform airlift and stirred-tank reactors in volumetric mass transfer coefficients and biomass productivity, making them scalable candidates due to rapid mixing and efficient aeration [49, 5]. Novel designs like the *Light Exchange Bubble-column (LEB)* merge internal light guides with bubble-column hydrodynamics to tackle light distribution limits, targeting gains in both productivity and energy efficiency [50-52].

Despite superior contamination control and productivity, closed PBRs demand significantly more energy for mixing, aeration, and temperature regulation driving operational costs above open ponds [53, 54]. Their economic viability hinges on offsetting these expenses with higher yields and premium product quality, often restricting use to high-value markets or hybrid systems. In essence, while PBRs offer advanced environmental control and performance, their

higher energy and capital costs necessitate ongoing innovation in design and cost-reduction to expand commercial adoption [54, 28].

2.3. Attachment or Biofilm-Based Cultivation

Biofilm-based microalgae cultivation are cells grow attached to surfaces rather than suspended in liquid, offers compelling advantages over conventional systems [55]. By achieving significantly *higher biomass concentrations* (often exceeding planktonic cultures), these systems slash water usage and simplify harvesting; cells can be scraped directly from substrates, bypassing energy-intensive dewatering [56]. Biofilms also enhance *photosynthetic efficiency* through optimized surface orientation for light exposure and direct atmospheric CO₂ absorption [55, 57].

Compared to open ponds and photobioreactors, biofilm systems demonstrate *competitive or superior productivity* pilot-scale rotating algal biofilm reactors, for example, achieve yields up to 31 g dry weight/m²/day, outpacing typical open ponds [58]. Their *energy demands are lower* (~0.87 W/m²) due to minimal mixing needs, while *reduced culture volumes* drastically improve water-use efficiency. However, scalability remains constrained by available attachment surface area and species-specific biofilm formation capabilities, demanding strategic substrate selection and design innovation [59]. In essence, biofilm cultivation excels in biomass density, harvesting ease, and resource efficiency, positioning it as a sustainable complement or alternative to traditional methods [60]. Overcoming scaling and species adaptability barriers will unlock its full potential.

3. Technological Advance in Cultivation

Recent technological advances in microalgal cultivation have significantly enhanced productivity, sustainability, and process control, driving the field toward commercial viability and integration into a bioeconomy [32, 61]. Key innovations include Optimization of cultivation parameters, Innovative reactor designs, Automation and monitoring technologies and Light management.

3.1. Optimization of Cultivation Parameters

Optimizing growth parameters light, temperature, pH, and nutrients is essential for maximizing microalgal biomass and valuable metabolites. Light powers photosynthesis but requires careful balancing: intensity must reach the *photosynthetic saturation point* without causing *photoinhibition* that damages cellular machinery [32, 62]. Spectral quality matters too; tailored LED wavelengths can boost growth and compound synthesis. Temperature critically influences enzymes and metabolism, with most species thriving at 20-30 °C; deviations slash productivity [63]. Similarly, pH (typically 7-9 for optimal growth) governs nutrient uptake and cellular

functions, though some algae tolerate extremes [64].

The *nutrient matrix* demands precise calibration nitrogen, phosphorus, and trace elements must avoid both starvation and toxic buildup [65]. Studies confirm optimized nitrogen/phosphate ratios dramatically accelerate growth. Equally crucial are *CO₂ concentration* for carbon supply and *mixing efficiency* for mass transfer, while cultivation periods and stirring speeds require species-specific tuning [66].

Today, *AI-driven sensors and automated controls* dynamically adjust these parameters in real-time, revolutionizing efficiency and scalability. Ultimately, dialing in these key growth parameters delivers high-yield, consistent-quality microalgae from lab benches to industrial photobioreactors [67].

3.2. Innovative Reactor Designs

Cutting-edge photobioreactor (PBR) designs are revolutionizing microalgae cultivation by tackling core challenges in light distribution, gas exchange, and process control, ultimately boosting biomass productivity and sustainability [44]. *Tubular PBRs* leverage transparent tubes arranged in serpentine or helical layouts to maximize light-exposed surface area while enabling efficient circulation for nutrients and gases [68]. *Flat-panel systems* feature thin, vertical growth chambers that optimize light penetration and mixing, often enhanced with reflective surfaces or internal illumination to amplify photosynthetic efficiency [69]. *Bubble-column and airlift reactors* achieve high mass transfer rates with minimal energy by using rising gas bubbles for both aeration and mixing. Meanwhile, *biofilm-based PBRs* cultivate microalgae on membranes or surfaces, enabling exceptional biomass density, simplified harvesting, and integrated wastewater treatment [70].

Recent breakthroughs push these frontiers further: projects like *BREVEL* integrate optical fibers for internal light delivery slashing costs by up to 90% while dramatically increasing yields [71]. *Automation* advances (real-time monitoring, machine learning, and image analysis) dynamically fine-tune growth conditions. Novel *modular designs* also enable synergistic systems, such as combining microalgae cultivation with aquaculture wastewater remediation to close resource loops [72]. Together, these innovations overcome historical barriers like light limitation, contamination risks, energy intensity, and scalability advancing toward economically viable, high-yield production for biofuels, nutraceuticals, and environmental applications.

3.3. Automation and Monitoring Technologies

Automation and smart monitoring are now indispensable for optimizing microalgal cultivation and enabling precise environmental control while boosting productivity [32, 73]. Advanced systems integrate *real-time sensors* that continuously track pH, dissolved oxygen, salinity, temperature, and biomass concentration eliminating manual checks and ena-

bling dynamic adjustments [74, 32]. For instance, automated photobioreactors paired with *data acquisition platforms like LabVIEW* leverage pH, DO, and salinity sensors to monitor culture health and predict growth trajectories [75]. Complementing this, *vision systems* analyze culture density and color shifts through image processing, providing non-invasive physiological insights.

Automation extends critically to harvesting, where emerging continuous/semi-continuous separation designs slash labor needs and prevent culture stagnation directly addressing a major scalability bottleneck [76, 32]. *IoT-enabled incubators* and smart platforms dynamically tune lighting (intensity/photoperiod), nutrient dosing, and CO₂ injection based on live sensor feedback, maximizing photosynthesis and metabolite yields [77, 75]. Meanwhile, *machine learning algorithms* predict growth patterns, flag contamination early, and refine operational parameters, driving more resilient and efficient cultivation. Collectively, these innovations elevate yield consistency while cutting operational costs and energy demands, key advancements for scalable, sustainable microalgae production in biofuels, functional foods, pharmaceuticals, and environmental remediation [76, 78].

3.4. Light Management

Effective light management is pivotal for optimizing microalgal cultivation, directly governing photosynthetic efficiency, biomass productivity, and metabolite synthesis [79]. This demands precise calibration of light intensity, spectral quality, duration, and distribution to maximize growth while combatting photoinhibition and energy waste. Innovations like *internal illumination systems* optical fibers or hollow light guides embedded within photobioreactors deliver photons deeper into dense cultures, overcoming self-shading and boosting light penetration [80, 71]. *Spectral tuning* via programmable LEDs targets wavelengths aligned with microalgal pigments (e.g., chlorophylls, carotenoids), enhancing light-use efficiency and steering metabolite profiles [81].

Beyond hardware, *dynamic light regimes* replicate natural variability: flashing sequences and photoperiod modulation reduce photodamage while optimizing energy conversion [82, 45]. Reactor design also plays a key role *ultra-thin flat-panel system* minimize light-path distances to elevate biomass concentration. Critically, light strategies must integrate temperature control, as excess irradiance induces thermal stress [45]. Computational modeling further refines approaches by simulating light scattering within cell aggregates and biofilms.

Despite microalgae's innate adaptability, industrial-scale cultivation introduces rapid light fluctuations (from mixing and cell density) that suppress photosynthetic efficiency [83, 84]. Emerging *genetic engineering* solutions address this by trimming photosynthetic antennae and modifying regulatory pathways to enhance high-light resilience. Ultimately, integrated light management merging reactor

engineering, smart lighting, and biological optimization proves essential for economically viable, high-yield microalgal production [85].

4. Strain Improvement and Genetic Engineering

Genetic engineering and strain improvement now stand at the forefront of advancing microalgal biotechnology, driving breakthroughs in biomass yield, stress resilience, and precision metabolite production [86–88]. With *whole-genome sequencing* completed for over 40 microalgal species, next-generation sequencing and bioinformatics tools empower comprehensive genomic analysis revealing key metabolic genes and regulatory elements ripe for engineering [89, 90]. Researchers strategically target three cellular compartments (*nucleus*, *mitochondria*, *chloroplasts*) to rewire pathways for lipids, pigments, and high-value bioactives.

Critical to this progress are *transformation techniques* like electroporation, glass bead agitation, and microfluidic electroporation, which successfully deliver foreign DNA into workhorse strains such as *Chlamydomonas reinhardtii*, *Scenedesmus obliquus*, and *Nannochloropsis* [91]. While *random mutagenesis* (via chemicals/UV/radiation) still generates mutants with enhanced CO₂ tolerance or metabolite yields, its instability limitations highlight the superiority of precision tool [92].

Targeted genome editing has revolutionized the field: CRISPR/Cas9 now dominates due to its simplicity, multiplex capability, and stable expression eclipsing older ZFNs and TALENs in tailoring lipid accumulation, stress resistance, and secondary metabolite pathways [93, 67]. Complementing this, *transcriptional engineering* modulates transcription factors to orchestrate multiple genes simultaneously, expanding our toolkit for metabolic optimization [94]. Collectively, these advances forge robust, high-performance strains tailored for commercial-scale biofuels, nutraceuticals, pharmaceuticals, and environmental applications propelling microalgae from lab curiosity to industrial reality [95].

5. Co-Cultivation and Integrated System

Co-cultivation and integrated systems mark a promising frontier in microalgal biotechnology, overcoming monoculture limitations by harnessing synergies between microalgae and bacteria, fungi, or other algal species [76]. These partnerships boost nutrient recycling, fortify contamination resistance, and elevate biomass and metabolite yields. In microalgal-bacteria consortia particularly effective in wastewater treatment mutualism thrives: bacteria supply vitamins and growth cofactors while microalgae provide oxygen and organic carbon, creating robust biomass production [96, 97].

Microalgae-fungi co-cultures excel in harvesting efficiency, where fungal mycelia bind microalgae into co-pellets through electrostatic binding and sticky secretions, dramatically simplifying biomass recovery [98]. These consortia also enhance wastewater remediation, outperforming monocultures in removing chemical oxygen demand (COD) and nutrients. Similarly, pairing complementary microalgal species leverages metabolic diversity to increase yields and environmental adaptability [99, 100].

Integrated systems compound these benefits by merging microalgal cultivation with wastewater treatment and CO₂ capture transforming waste streams into low-cost nutrients and carbon sources [101, 102]. Optimizing variables like inoculum ratios, light intensity, and CO₂ levels in co-cultures has proven critical for maximizing biomass and lipids while slashing downstream energy costs [98]. Ultimately, these approaches deliver more efficient, sustainable, and economically viable microalgae platforms for biofuels, bioremediation, and high-value bioproducts across industries [103].

6. Down Stream Processing Innovation

Downstream processing innovations are revolutionizing microalgal bioprocessing, making harvesting, cell disruption, extraction, and purification more efficient, sustainable, and economically viable [104]. Recent advances prioritize *green extraction methods* like supercritical CO₂, ultrasound-assisted, and microwave-assisted techniques boosting yields of lipids, pigments, and bioactive compounds while slashing environmental impacts compared to traditional solvents [105, 106]. To tackle notoriously resilient microalgal cell walls, novel *mechanical disruption* (bead milling, high-pressure homogenization) delivers superior product release, while *enzymatic hydrolysis* emerges as a gentler alternative that preserves delicate biomolecules [104, 107].

Nanomaterials now play a pivotal role, enhancing harvesting through nano-enabled sedimentation, flocculation, and flotation dramatically cutting energy use and operational costs [108]. The shift toward *integrated biorefineries* maximizes value by fractionating biomass into biofuels, nutraceuticals, cosmetics ingredients, and specialty chemicals from a single feedstock. Automation and *continuous processing* (like volatile compound stripping) further streamline workflows [109].

Despite progress, scaling these technologies while balancing cost-efficiency and sustainability remains challenging. Rigorous *life-cycle assessments and techno-economic analyses* are now essential to refine processes and ensure market competitiveness. Collectively, these innovations bridge the gap between microalgal biomass production and commercial viability, enabling sustainable, profitable manufacturing of high-value microalgal products [59].

7. Challenges in Scaling Up

Scaling microalgal cultivation confronts interconnected barriers that stall commercial viability. Chief among these is *high production cost* (€290-570 per kg dry biomass), driven by steep capital investments and operational expenses for liquid handling, lighting, temperature control, cleaning, and harvesting [110-112]. *Contamination risks*, especially in open ponds demand robust management to counter invasive species and culture crashes [5]. Scaling also intensifies challenges in *nutrient/CO₂ supply*, requiring integration with wastewater or flue gases to cut costs and boost sustainability [36]. Outdoor systems face compounded *light/temperature variability*, undermining growth consistency, while *energy-intensive harvesting* devours budgets often becoming the costliest production phase [113].

Adding complexity, a *shortage of skilled phycology and engineering experts* hampers operations, though new training programs aim to bridge this gap. *Social acceptance hurdles and regulatory uncertainty* particularly for food/feed applications further cloud market prospects. Achieving economic viability hinges on *economies of scale, multi-product biorefineries*, and synergies with wastewater/CO₂ capture to slash inputs and environmental footprints.

Critically, *life cycle assessments (LCAs)* and *techno-economic analyses (TEAs)* underscore that overcoming these bottlenecks demands integrated solutions: technological innovation, supportive policies, and cross-sector collaboration to unlock sustainable large-scale microalgal production.

8. Future Prospectives and Emerging Trends

The future of microalgal biotechnology shines brightly, pivoting toward sustainable, high-value applications through transformative innovations. *Advanced genetic tools* particularly CRISPR-based systems like Cas9 and Cas12a now enable surgical precision in tailoring strains [67, 114]. In Nanochloropsis, these editors doubled lipid productivity and amplified carbon fixation, accelerating commercialization [115]. Their capacity for *multiplexed gene editing* and transcriptional control further streamlines strain development for diverse industries.

Simultaneously, *AI and machine learning* are revolutionizing cultivation: algorithms digest sensor data to optimize light, nutrients, and CO₂ in real-time, slashing operational costs while boosting yields and preempting contamination [76]. This intelligence layer is making large-scale production economically feasible.

The rise of *integrated biorefineries* marks another critical shift, transforming single feedstocks into multiple premium products biofuels, nutraceuticals, cosmetics, fragrances, and biomaterials [116-118]. By valorizing every biomass component and coupling with wastewater treatment/carbon cap-

ture, these systems anchor circular bioeconomies while improving margins.

Supportive *policy frameworks* now incentivize sustainable practices, including carbon credits, catalyzing investment [119]. Meanwhile, *surging consumer demand* for natural, functional ingredients is opening lucrative markets in cosmetics, nutraceuticals, and green materials. Collectively, these advances cement microalgae's role as versatile, sustainable biofactories poised to redefine green biotechnology.

9. Conclusion

In conclusion, microalgae present immense potential as sustainable, versatile bioresources poised to drive the future bioeconomy. Their rapid growth, metabolic diversity, and waste-stream utilization capability position them as pivotal producers of biofuels, nutraceuticals, cosmetics, and environmental solutions notably wastewater treatment and CO₂ sequestration. Advances across cultivation technologies, genetic engineering, automation, and integrated biorefineries are steadily dismantling current hurdles in productivity, contamination, and economic viability. Meanwhile, emerging trends like synthetic biology, AI-driven process optimization, and supportive policy frameworks accelerate microalgal biotechnology's transition from lab research to commercial reality. By leveraging these innovations and resolving scale-up bottlenecks, microalgae can critically advance a circular, carbon-neutral, resource-efficient bioeconomy, meeting urgent global demands for sustainable energy, health, and environmental stewardship.

Abbreviations

AI	Artificial Intelligence
COD	Chemical Oxygen Demand
CRISPR/Cas9	Clustered Regularly Interspaced Short Palindromic Repeats/ Cas9
DNA	Deoxyribonucleic Acid
g	gram
HRAPs	High-Rate Algal Ponds
LCAs	Life Cycle Assessments
LEB	Light Exchange Bubble-column
LED	Light Emitting Diodes
PBRs	Photobioreactors
TALENs	Transcription Activator-Like Effector Nucleases
TEAs	Techno-Economic Analyses
ZFNs	Zinc Finger Nucleases

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Alebachew Molla: Conceptualization, Methodology, Visualization, Resources, Writing - original draft

Gedif Meseret: Investigation, Validation, Supervision

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Conflicts of Interest

The authors declare no conflicts of interest.

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