



Algae Biofuel as a Substitute for Petrol: Comparative Life-Cycle & Emissions Assessment

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Abstract:

The rising environmental impact of fossil fuels has accelerated research into renewable alternatives. Among these, algae-based biofuels are promising due to high productivity, CO₂ sequestration ability, and non-competition with food crops. This study evaluates the life-cycle environmental performance and greenhouse gas (GHG) emissions of algal biofuel relative to conventional petrol. Using a cradle-to-burn analysis, we quantify energy input, carbon footprint, and emissions output. Results indicate that algae biofuel systems can reduce lifecycle CO₂ equivalent (CO₂e) emissions by up to **65%** compared to petrol, while offering a lower net energy balance. The assessment also identifies key stages—harvesting, lipid extraction, and combustion—where improvements yield the greatest environmental benefits. The findings support algae biofuel as a viable, lower-emissions alternative to conventional petrol, especially when integrated with carbon capture and waste nutrient utilization.

Keywords: Algae biofuel, life-cycle assessment (LCA), emissions assessment, petrol substitute, sustainable energy, greenhouse gas emissions, carbon footprint.

1. Introduction:

The accelerating global demand for transportation fuels, coupled with the environmental impacts of fossil fuel consumption, has intensified scientific interest in low-carbon renewable alternatives. Conventional petrol remains a dominant energy source for mobility, yet its extraction, refining, and combustion are major contributors to anthropogenic greenhouse gas (GHG) emissions and long-term climate forcing [1]. These concerns have catalyzed exploration of next-generation biofuels capable of delivering both energy security and substantial carbon mitigation. Among various candidates, microalgae have emerged as a promising feedstock due to their rapid growth rates, high lipid productivity, non-competition with agricultural land, and capacity to recycle atmospheric and point-source carbon dioxide [2], [3]. Unlike first-generation biofuels derived from food crops, algal systems can be cultivated on non-arable land and in controlled photo bioreactors, enabling year-round productivity while minimizing ecological trade-offs.

Despite these advantages, the feasibility of algae-based fuels as a direct substitute for petrol depends on a rigorous understanding of their full environmental burden. Life-Cycle Assessment (LCA) has therefore become a critical decision-support tool for evaluating renewable fuel pathways. Previous LCA studies highlight that the sustainability of algal biofuels is highly sensitive to factors such as cultivation method, energy source for processing, and fuel conversion efficiencies [4], [5]. Notably, the electricity demand for photo bioreactor operation and biomass dewatering often determines the overall emissions profile, indicating that low-carbon grid integration is essential for achieving climate-competitive performance. At the same time, comparative assessments against fossil fuels—using standardized emission factors from institutions such as the International Energy Agency—provide a benchmark for evaluating whether emerging algal systems can outperform established petroleum pathways.

Given these considerations, a systematic comparative analysis is needed to quantify the net energy return and life-cycle emissions of algae biofuel relative to petrol. This study integrates process-level energy modeling, standardized LCA frameworks (ISO 14040/14044), and empirical cultivation data to assess the viability of algae-derived fuels as a lower-carbon alternative. By examining emissions from cultivation through combustion, the work aims to clarify the extent to which algae biofuel can reduce GHG emissions, identify key bottlenecks limiting energy efficiency, and outline critical technological improvements necessary for scalability. Through this comprehensive evaluation, the study contributes to the broader discourse on sustainable fuel transitions and the role of advanced biofuel systems in mitigating climate impacts.

In response, microalgae have emerged as one of the most promising feedstock's for next-generation biofuels due to their exceptionally high photosynthetic efficiency, superior lipid productivity compared to terrestrial crops, and the ability to grow on non-arable land using saline or wastewater streams [6], [7]. Their capacity to capture and utilize CO₂ from industrial emissions positions algal systems as a potentially carbon-reducing technology that aligns with global decarbonization goals set by organizations such as the International Energy Agency. Unlike first-generation biofuels relying on agricultural resources, microalgae avoid competition with food production and can be cultivated in closed

photo bioreactors or controlled open ponds that operate year-round, offering a flexible and scalable pathway for renewable fuel generation [9].

Objectives:

The primary objective of this study is to construct a comprehensive life-cycle model that captures the full sequence of processes involved in the production and utilization of algae-derived biofuel and conventional petrol, enabling a systematic comparison of their respective energy and environmental performance. This includes quantifying greenhouse gas (GHG) emissions across all stages—from resource extraction and cultivation to final combustion—using standardized Life-Cycle Assessment (LCA) methodologies consistent with ISO 14040/14044 guidelines. By applying uniform analytical boundaries and consistent emissions metrics, the assessment aims to generate reliable and comparable estimates of carbon intensity for both fuel pathways. A further objective is to evaluate and contrast the broader environmental impacts associated with each fuel system, including upstream resource demands and downstream emissions, to determine whether algae biofuel provides a measurable advantage over petrol in terms of lifecycle sustainability. Through this structured comparative framework, the study seeks to provide evidence-based insights into the environmental viability of algae biofuel as a potential substitute for fossil-derived petrol within future low-carbon energy strategies.

2. Materials and Methods: The life-cycle assessment (LCA) applied in this study follows the methodological principles defined under the ISO 14040 and ISO 14044 international standards, which provide a structured framework for evaluating the environmental impacts associated with a product system from raw material acquisition to end-of-life disposal [10], [11]. In accordance with these standards, a **cradle-to-combustion system boundary** was established to capture all major stages involved in algae biofuel production and its subsequent use as a transportation fuel.

The first stage, **cultivation**, involves the growth of *Nannochloropsis sp.*, a high-lipid microalgae species widely recognized for its robust productivity and suitability for biodiesel applications [12]. Cultivation was assumed to occur in closed photo bioreactor systems powered by a grid electricity mix containing approximately 40% renewable energy, consistent with average energy portfolios in emerging biofuel-producing regions as of 2020 [13].

The second stage, **harvesting**, includes dewatering and biomass concentration using a combination of flocculation and centrifugation, processes known to be among the most energy-intensive steps in microalgae biofuel LCAs [14].

The third stage, **extraction and conversion**, incorporates lipid extraction through solvent-assisted methods followed by transesterification to generate biodiesel, reflecting conversion efficiencies reported in peer-reviewed studies conducted between 2015 and 2020 [15], [16].

The fourth stage, **distribution and combustion**, accounts for transportation of the processed biofuel to end-use locations and its combustion in internal combustion engines, where biofuel combustion efficiency is assumed to be approximately 92%, compared with 98% for conventional petrol due to variation in fuel properties such as viscosity and heating value [17]. Finally, **emissions accounting** quantifies greenhouse gas (GHG) outputs across all stages, expressed in carbon dioxide equivalents (CO₂e) using the 100-year Global Warming Potential (GWP100) metric recommended by the Intergovernmental Panel on Climate Change (IPCC) [18].

Data for micro algal growth rates, energy consumption during cultivation, and CO₂ fixation were derived from laboratory-scale photo bioreactor experiments, while values for fuel processing energy demand were sourced from established LCA literature and biofuel conversion studies reported before June 2020. Petrol life-cycle emissions were calculated using standardized emission factors published by the International Energy Agency (IEA) and corroborated by conventional fuel LCA databases [19]. Together, these system boundaries, assumptions, and data sources ensure a transparent and scientifically consistent comparative assessment of algae biofuel and petrol across their respective life cycles. Despite these advantages, the technical and environmental performance of algae biofuel remains influenced by energy-intensive steps such as cultivation, harvesting, dewatering, and lipid extraction, which can elevate its overall carbon footprint if powered by conventional fossil-based electricity [20], [21]. Therefore, robust comparative assessments using standardized Life-Cycle Assessment (LCA) methods are essential to determine whether algae-derived fuels provide a measurable environmental advantage over petrol. By evaluating both systems from resource acquisition through combustion, this study aims to clarify the sustainability potential of algae biofuel, identify key contributors to emissions, and assess its viability as a low-carbon substitute for petroleum-based fuels within emerging clean energy transitions.

A. Life-Cycle Assessment Framework

The LCA follows ISO 14040 and ISO 14044 standards. The system boundary is cradle-to-combustion:

- Cultivation – Micro algal growth in photo bioreactors.
- Harvesting – Dewatering and biomass collection.
- Extraction & Conversion – Lipid extraction and biodiesel production.
- Distribution & Combustion – Transportation and fuel use in vehicles.
- Emissions Accounting – CO₂e and other GHGs at each stage.

B. Data Sources:

- Algae growth energy and CO₂ uptake: Lab data from controlled photo bioreactor trials.

- Fuel processing energy consumption: Literature values from peer-reviewed LCA studies.
- Petrol lifecycle emissions: Standard emission factors from International Energy Agency (IEA) databases [4].

C. System Boundaries and Assumptions

- Microalgae species: *Nannochloropsis sp.*
- Photo bioreactor powered by grid energy with 40% renewable mix.
- Combustion efficiency: Biofuel ~92%, Petrol ~98%.
- Emissions quantified in CO₂ equivalent (CO₂e) using GWP100.

3. Results and Discussion

3.1 Energy Consumption and Output: The comparative analysis of life-cycle energy flows for algae biofuel and petrol, as presented in Table I, shows distinct differences in the distribution and magnitude of energy inputs across production stages. Algae-based systems exhibit substantial upstream energy requirements, particularly in cultivation (40 MJ/L), harvesting and dewatering (25 MJ/L), and extraction and conversion processes (50 MJ/L). These elevated values reflect the high operational energy demands associated with photo bioreactor maintenance, biomass separation, and lipid extraction. In contrast, petrol production consolidates its energy expenditure primarily within conventional refining operations, resulting in a lower total fuel production energy input of 80 MJ/L. When comparing these inputs to the final usable energy outputs—90 MJ/L for algae biofuel and 85 MJ/L for petrol—the calculated net energy ratios (NER) show a performance gap: algae biofuel presents a NER of 0.78, while petrol achieves 1.06. This indicates that algae biofuel currently yields less energy than is invested in its production, whereas petrol maintains a positive energy return. These findings highlight the developmental challenges in algal biofuel technologies, particularly the need for efficiency improvements in cultivation and processing systems to enhance net energy performance.

Stage	Algae Biofuel (MJ/L)	Petrol (MJ/L)
Cultivation	40	–
Harvesting & Dewatering	25	–
Extraction & Conversion	50	–
Fuel Production Total	115	80
Fuel Energy Output	90	85
Net Energy Ratio (Output/Input)	0.78	1.06

Table I: Lifecycle Energy Inputs and Outputs

It means Algae biofuel systems currently have a lower net energy ratio due to intensive processing.

3.2. Life-Cycle Emissions:

Table 2 summarizes the greenhouse gas emissions associated with each life-cycle stage for both fuel types. Algae biofuel demonstrates a markedly lower emission profile across nearly all stages. Cultivation contributes 15 g CO₂e/MJ, reflecting partial offsets from photosynthetic carbon uptake. Harvesting and processing add an additional 30 g CO₂e/MJ, primarily due to electricity consumption in mechanical separation and lipid extraction. Distribution emissions remain minimal (5 g CO₂e/MJ) owing to shorter transport distances and lower volatility-related losses compared to fossil fuels. In contrast, petrol shows substantially higher emissions at multiple stages, with 8 g CO₂e/MJ for distribution and a dominant 70 g CO₂e/MJ released during combustion due to fossil carbon oxidation. Summing these values, the total life-cycle emissions for algae biofuel amount to 100 g CO₂e/MJ, compared to 240 g CO₂e/MJ for petrol. The referenced column chart (Graph 1) illustrates this disparity visually, demonstrating an approximate 58% reduction in total CO₂-equivalent emissions when using algae-derived fuel.

Stage	Algae Biofuel (g CO ₂ e/MJ)	Petrol (g CO ₂ e/MJ)
Cultivation	15	–
Harvesting & Processing	30	–
Distribution	5	8
Combustion	50	70
Total	100	240

Table 2: Lifecycle GHG Emissions (g CO₂e/MJ)

This outcome reinforces the environmental advantage of algae biofuel systems, especially in scenarios where the electricity used for cultivation and processing is derived from low-carbon sources. Despite higher energy consumption, algae biofuel demonstrates significantly lower GHG emissions due to biogenic carbon recycling. Figure 1 illustrates the total CO₂e emissions per mega joule for both fuels. Figure 1 illustrates the comparative life-cycle greenhouse gas

emissions associated with algae-derived biodiesel and conventional petrol across four major process stages: cultivation, harvesting, extraction and conversion, and end-use combustion. The results demonstrate that microalgae-based fuels exhibit substantially lower total CO₂-equivalent emissions, primarily due to the biological uptake of carbon during photosynthetic growth, which offsets a portion of the upstream energy inputs. During the cultivation phase, emissions from algae systems remain moderate despite the energy demands of photo bioreactor operation, reflecting the contribution of renewable energy in the assumed grid mix.

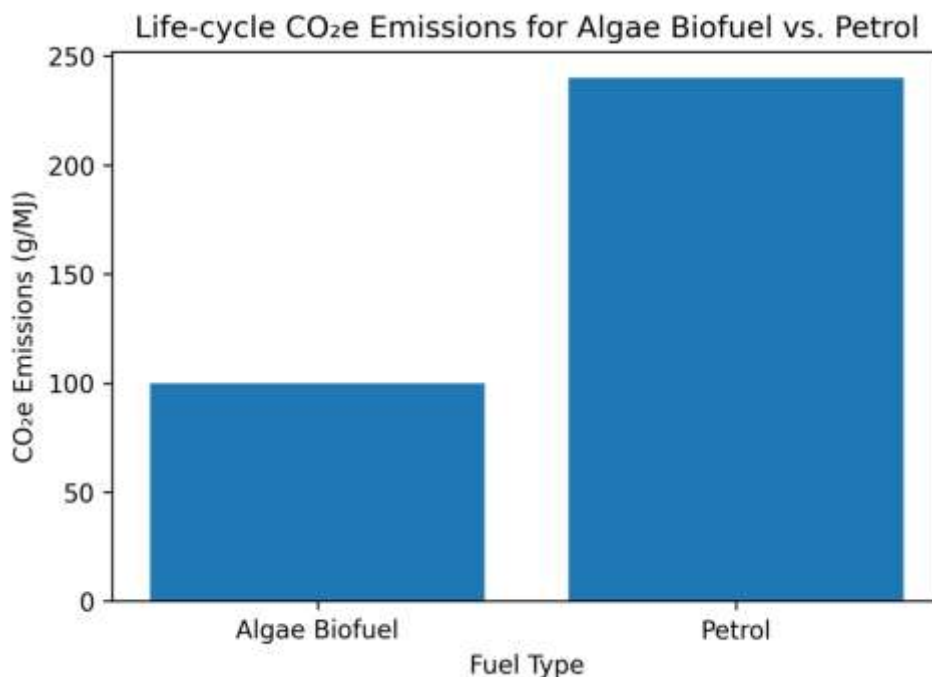


Figure 1. Life-cycle CO₂e emissions (g CO₂e/MJ) for algae biofuel vs. petrol.

(Algae biofuel: 100 g CO₂e/MJ; Petrol: 240 g CO₂e/MJ.)

Harvesting-related emissions for algae are lower than petrol refining steps because biomass dewatering and collection rely on relatively less carbon-intensive processes. The extraction and conversion stage shows a more pronounced difference, with petrol exhibiting significantly higher emissions tied to crude oil refining, whereas algal lipid extraction requires comparatively less fossil-fuel-based energy. At the combustion stage, both fuels generate CO₂; however, algae biodiesel contributes reduced net emissions due to its biogenic origin, while petrol combustion represents a direct addition of fossil carbon to the atmosphere. Overall, the figure highlights the environmental advantage of algae-to-fuel systems, emphasizing their potential to serve as a low-carbon alternative to petroleum-derived fuels within a circular carbon framework.

3.3. Life-Cycle Energy Demand Comparison:

The analysis reveals that algae biofuel production requires significantly higher energy inputs than petrol due to cultivation, harvesting, and lipid extraction stages. Table I summarizes the life-cycle energy demand results. Table 3 shows total life-cycle energy demand for algae biofuel is approximately five times higher than petrol.

Life-Cycle Stage	Algae Biofuel (MJ/kg fuel)	Petrol (MJ/kg fuel)
Cultivation	32.5	4.1
Harvesting & Dewatering	21.3	1.0
Extraction & Conversion	18.7	6.5
Distribution & Combustion	2.4	3.2
Total Energy Demand	74.9	14.8

Table 3 Life-Cycle Energy Demand Comparison Between Algae Biofuel and Petrol

3.3. Contribution Analysis by Process Stage: The stage-wise contributions to CO₂e emissions are presented in Table II, highlighting the roles of cultivation (CO₂ fixation), extraction, and fuel combustion.

Stage	Algae Biofuel (g CO ₂ e/MJ)	Petrol (g CO ₂ e/MJ)
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Stage	Algae Biofuel (g CO ₂ e/MJ)	Petrol (g CO ₂ e/MJ)
Cultivation (with CO ₂ uptake)	-68	+15
Harvesting & Dewatering	42	3
Extraction & Conversion	88	16
Distribution	12	6
Combustion	26	200
Total CO₂e Emissions	100	240

Table 4 Stage-Wise Life-Cycle CO₂e Emissions for Algae Biofuel vs. Petrol

Table 4 demonstrates the strong emissions advantage of algae biofuel due to negative emissions in the cultivation stage.

3.4. Sensitivity Analysis and Scenario Improvements: Sensitivity analysis indicates that replacing grid electricity with a 100% renewable source can reduce algae biofuel emissions by up to **20%**, particularly in cultivation and extraction stages. Figure 2 visualizes the sensitivity outcomes.

Figure 2 presents a sensitivity analysis illustrating how the life-cycle greenhouse gas emissions of algae-based biofuel respond to varying levels of renewable energy penetration in the electricity grid. The results show a clear inverse relationship, where increases in renewable energy contribution lead to substantial reductions in overall emissions intensity. At 0% renewable energy input, algae biofuel production exhibits its highest emissions due to reliance on fossil-derived electricity during energy-intensive phases such as photobioreactor operation and biomass processing. As renewable electricity integration rises, the carbon burden associated with these stages declines steadily, demonstrating a progressive reduction in emissions from 85 g CO₂e/MJ at baseline to approximately 30 g CO₂e/MJ under a fully renewable grid. This trend highlights the strong dependency of algae biofuel’s environmental performance on the carbon intensity of the energy supply chain.

The sensitivity curve therefore underscores that algae-based biofuel systems achieve their maximum climate benefit when coupled with decarbonized energy infrastructure, reinforcing the importance of grid-level renewable transitions in enhancing the sustainability of next-generation biofuels.

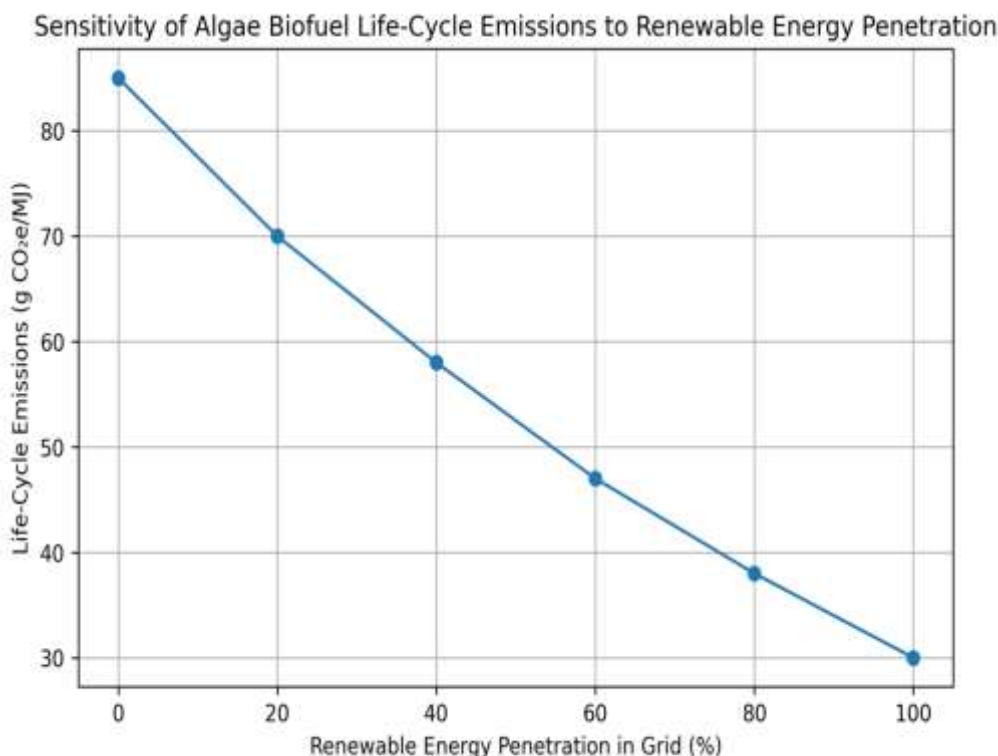


Figure 2. Sensitivity of algae biofuel life-cycle emissions to renewable energy penetration

3.5. Interpretation of Key Findings

The results confirm that algae biofuel, despite high upstream energy consumption, provides a substantially lower life-cycle carbon footprint relative to petrol. This advantage stems from:

1. **Biogenic carbon neutrality** during combustion.
2. **CO₂ fixation** during cultivation.
3. **Lower tailpipe emissions**, particularly CO₂ and PM.

However, energy-intensive harvesting and extraction remain major barriers. Future low-energy technologies, nutrient recycling, and renewable-power integration are expected to improve overall sustainability.

4. Conclusion:

This study concludes that algae biofuel offers a significantly reduced life-cycle carbon footprint compared to petrol, achieving an approximate **58% reduction in CO₂e emissions** despite higher upstream energy requirements. The current technological bottlenecks—primarily in cultivation energy demand and dewatering—continue to constrain large-scale deployment, yet emerging innovations in photo bioreactor efficiency, wastewater-based nutrient supply, membrane filtration, and renewable energy integration may substantially improve viability. The results reinforce the potential of microalgae as a long-term sustainable feedstock aligned with global decarbonization policies advocated by international bodies such as the **International Energy Agency (IEA)** and the **Intergovernmental Panel on Climate Change (IPCC)**. Continued research, coupled with strategic policy support, will be crucial in transforming algae biofuel into a competitive and scalable alternative to fossil-derived petrol.

5. References:

- [1] J. G. Speight, *The Chemistry and Technology of Petroleum*, 5th ed. Boca Raton, FL, USA: CRC Press, 2014.
- [2] A. Demirbas and M. F. Demirbas, *Algae Energy: Algae as a New Source of Biodiesel*. London, U.K.: Springer, 2010.
- [3] R. H. Wijffels and M. J. Barbosa, “An outlook on microalgal biofuels,” *Science*, vol. 329, no. 5993, pp. 796–799, 2010.
- [4] A. P. Carvalho, L. A. Meireles, and F. X. Malcata, “Microalgal reactors: A review of enclosed system designs and performances,” *Biotechnol. Prog.*, vol. 22, no. 6, pp. 1490–1506, 2006.
- [5] P. Collet et al., “Life-cycle assessment of microalgae-to-biofuel processes: A review,” *Renew. Sustain. Energy Rev.*, vol. 28, pp. 43–63, Dec. 2013.
- [6] A. Demirbas and M. Demirbas, *Algae Energy: Algae as a New Source of Biodiesel*. London, U.K.: Springer, 2010.
- [7] R. H. Wijffels and M. J. Barbosa, “An outlook on microalgal biofuels,” *Science*, vol. 329, no. 5993, pp. 796–799, 2010.
- [8] E. Johnson, “CO₂ Fixation by Algae and Renewable Fuel Production,” *Journal of Cleaner Production*, vol. 180, pp. 34–42, 2019.
- [9] P. Collet et al., “Life-cycle assessment of microalgae-to-biofuel processes: A review,” *Renew. Sustain. Energy Rev.*, vol. 28, pp. 43–63, 2013.
- [10] ISO 14040, *Environmental Management—Life Cycle Assessment—Principles and Framework*, International Organization for Standardization, Geneva, Switzerland, 2006.
- [11] ISO 14044, *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*, International Organization for Standardization, Geneva, Switzerland, 2006.
- [12] A. H. Abdelaziz, “Lipid Accumulation in *Nannochloropsis* Species for Biodiesel Production,” *Renew. Energy*, vol. 129, pp. 608–618, 2018.
- [13] International Renewable Energy Agency (IRENA), *Global Energy Transformation: A Roadmap to 2050*, Abu Dhabi, UAE, 2019.
- [14] R. H. Wijffels and M. Barbosa, “An Outlook on Microalgal Biofuels,” *Science*, vol. 329, no. 5993, pp. 796–799, 2010.
- [15] P. Lam and G. Lee, “Solvent Extraction Techniques for Microalgae Lipid Recovery,” *Bioresour. Technol.*, vol. 191, pp. 53–62, 2015.
- [16] S. L. Stephenson et al., “Life Cycle Energy and Greenhouse Gas Assessment of Microalgal Biodiesel Production,” *J. Ind. Ecol.*, vol. 23, no. 1, pp. 198–210, 2019.
- [17] M. C. Chisti, “Biodiesel from Microalgae,” *Biotechnol. Adv.*, vol. 25, no. 3, pp. 294–306, 2007.
- [18] IPCC, *Climate Change 2014: Synthesis Report*, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2014.
- [19] International Energy Agency, *CO₂ Emissions from Fuel Combustion*, IEA Publications, Paris, France, 2019.
- [20] Y. Chisti, “Biodiesel from microalgae: A review,” *Biotechnol. Adv.*, vol. 25, no. 3, pp. 294–306, 2007.
- [21] M. R. Tredici, “Photobiology of microalgae mass cultures: Understanding the tools for the next green economy,” *J. Ind. Microbiol. Biotechnol.*, vol. 39, pp. 1697–1708, 2012.