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# Advanced Biofuels from Microalgae Cultivation: A Sustainability Perspective on Barriers and Enablers in the Adoption of Clean Technologies

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**Abstract:** The demand for a sustainable and renewable shift to global energy has led third-generation advanced biofuels to stand out as a strategic and relevant alternative to fossil fuels, thanks to their high sustainability and ability to reduce greenhouse gas emissions. Even with promising potential, technical, economic, and operational challenges persist, preventing commercial expansion and large-scale industry scalability. This review systematically highlights the main challenges and opportunities in implementing the microalgae-based advanced biofuels market, emphasizing a sustainability-focused approach. Using the PRISMA methodology, a final set of 59 articles was selected for review. A bibliometric analysis with the Biblioshiny tool was conducted to map the scientific landscape, verify core research concepts, and spot emerging trends. The study confirms that the four main barriers are technological, economic, market, and regulatory. Literature indicates that economic viability can be achieved through a biorefinery approach within the circular bioeconomy model, transitioning from simple, low-value biofuel production to a range of diversified bioproducts. To facilitate the transition, a four-pillar strategic roadmap is proposed, connecting research and development (R&D), economic incentives, and policy measures. This roadmap positions the advanced biofuel market from the microalgae value chain as a Blue Ocean Strategy, promoting a symbiotic dynamic for investors committed to sustainability and the circular economy.

**Keywords:** Advanced biofuels; Circular bioeconomy; Microalgae Cultivation; Strategic Roadmapping.

## 1. Introduction

As the world shifts away from fossil fuels, the primary contributor to greenhouse gases, with carbon dioxide accounting for approximately 60% of these emissions (Sadvakasova et al., 2023), advanced biofuels offer a promising strategic alternative. In particular, third-generation biofuels derived from microalgae are notable for their high sustainability potential. Ribeiro et al. (2015) suggests that biofuels from microalgae could represent 1% to 5% of global fuel use by 2030. These biofuels do not compete with food supplies, can absorb a significant amount of carbon dioxide (up to ten times more than land plants), and contain up to 70% lipids, making them highly effective for biofuel production (Hariram et al., 2025; Zhu et al., 2024)

Microalgae can be cultivated in two ways: in open pond systems and in closed systems using photobioreactors. In the open system (Razzak et al., 2024), as a simplified system, production can be on a large and industrial scale, ranging from 40 to 60 tons per year (Piyatilleke et al., 2025). Generally, the cultivation system uses running ponds; however, its fragility to external disturbances, such as uncontrollable and inconsistent nutrient stress; light reflection on the surface, inhibiting light entry into the system, and decreasing the photosynthetic capacity of the microalgae; eutrophication of the site, can reduce the amount of biomass produced compared to closed systems (Slegers et al., 2013). However, its low cost, also in relation to closed systems, makes it viable on an industrial level (Razzak et al., 2024). In closed photobioreactor systems, their adaptable controllability makes them a more precise and biomass-producing system; however, their low production scalability and high implementation and maintenance costs pose a challenge to scaling up the system to an industrial level (Laizu; Hassan; Ahmad, 2025).

Microalgae are photosynthetic unicellular microorganisms with a high capacity for carbon dioxide fixation and nutrient absorption, including phosphate and nitrate, resulting in the production of biomass. The biomass can be processed through mechanical extraction or transesterification, using solvents combined with reagent alcohol (Sun et al., 2024). Large-scale cultivation is a viable, sustainable alternative to non-renewable fossil fuels.

The production process for obtaining oil from microalgae begins with the cultivation of biomass, carried out in open systems, such as circular, rectangular or track-shaped ponds, equipped with mechanical paddles that ensure the movement of the medium, preventing the accumulation of stagnant water.

Once the cultivation cycle is complete, the biomass is separated through a flocculation process, in which chemical agents are added, and the pH is temporarily adjusted to promote the agglomeration of microalgae cells, facilitating the subsequent drying stage (Xin et al., 2026). The flocculated biomass can be subjected to drying using different methods, such as the solar dryer, which is less expensive and more efficient, or the drum flash system, which, although more efficient, has higher operating costs and is more commonly used in closed cultivation systems (Soares; Ferreira Martins; Gonçalves, 2019). The next step involves oil extraction, which is carried out using an organic solvent, typically hexane, to separate the crude oil from the dry biomass, allowing for its subsequent purification and use as a biofuel (S et al., 2025).

Finally, the crude oil undergoes the transesterification process, in which a chemical reaction occurs between the triglycerides present in the oil and an alcohol, typically methanol or ethanol, in the presence of an alkaline catalyst, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) (Sun et al., 2024). The reaction results in the formation of methyl or ethyl esters, which constitute biodiesel, and glycerol as a byproduct.

These photosynthetic microorganisms, abundant in nature, are classified as third-generation feedstock for advanced biofuels, as they do not directly compete with the food industry and do not require agricultural areas typically used for food production (Maliha; Abu-Hijleh, 2023). According to Future Market Insights, the global market for microalgae and their derivatives is projected to grow significantly, potentially reaching US$25.4 billion by 2033. Despite this promising scenario, technical, economic, and operational challenges remain, hindering large-scale commercial expansion.

The advanced biofuel provided by microalgae biomass market has the potential to remain economically sustainable due to its ability to capture carbon dioxide from the atmosphere, converting it into oxygen and biomass through photosynthesis (Picknell et al., 2025). The process not only helps mitigate greenhouse gas emissions but also enables the production of biofuels and other sustainable bioproducts. Environmental advantages can be strategically incorporated into the business model, aligning with key global environmental agendas, such as Sustainable Development Goals (SDGs) 7 – Affordable and Clean Energy; SDG 9 – Industry, Innovation and Infrastructure; SDG 12 – Responsible Consumption and Production; SDG 13 – Climate Action; SDG 14 – Life Below Water, as well as international decarbonization commitments. In this way, the microalgae sector positions itself as an innovative solution that promotes the generation of economic value combined with sustainability (Gallego et al., 2025), creating market opportunities and guaranteeing financial returns for companies involved in this segment.

These new market opportunities can be interpreted in accordance with the Blue Ocean Strategy, which involves developing a microalgae production chain as a value innovation strategy capable of establishing a symbiotic economic dynamic among society, the environment, and investors. Not only are financial returns being considered, but also the promotion of environmental and social benefits, thereby consolidating a sustainable business model aligned with contemporary demands for low-carbon solutions and the bioeconomy (Vickram et al., 2025).

The Blue Ocean Strategy establishes a conceptual distinction between so-called “blue oceans” and “red oceans” (Kim; Mauborgne, 2005). Blue oceans represent unexplored market spaces characterized by the absence of direct competition, where organizations focus on creating demand, rather than competing for it, through value innovation. On the other hand, red oceans correspond to existing, highly competitive, and saturated markets, in which companies compete intensely for shares of previously established demand, facing higher barriers to entry and less room for differentiation (Awladthani et al., 2023).

Given this context, it is essential to emphasize the importance of adopting strategies that facilitate the consolidation of this market, in addition to addressing the technical aspects of microalgae cultivation, thereby contributing to the efficient creation and structuring of new markets. Therefore, the objective of this study is to identify the challenges and opportunities for implementing the microalgae cultivation market, with a focus on the production of advanced biofuels, based on a systematic analysis of the literature. This analysis considers the technological, regulatory, and economic aspects that influence the adoption of clean technologies.

## 2. Methods

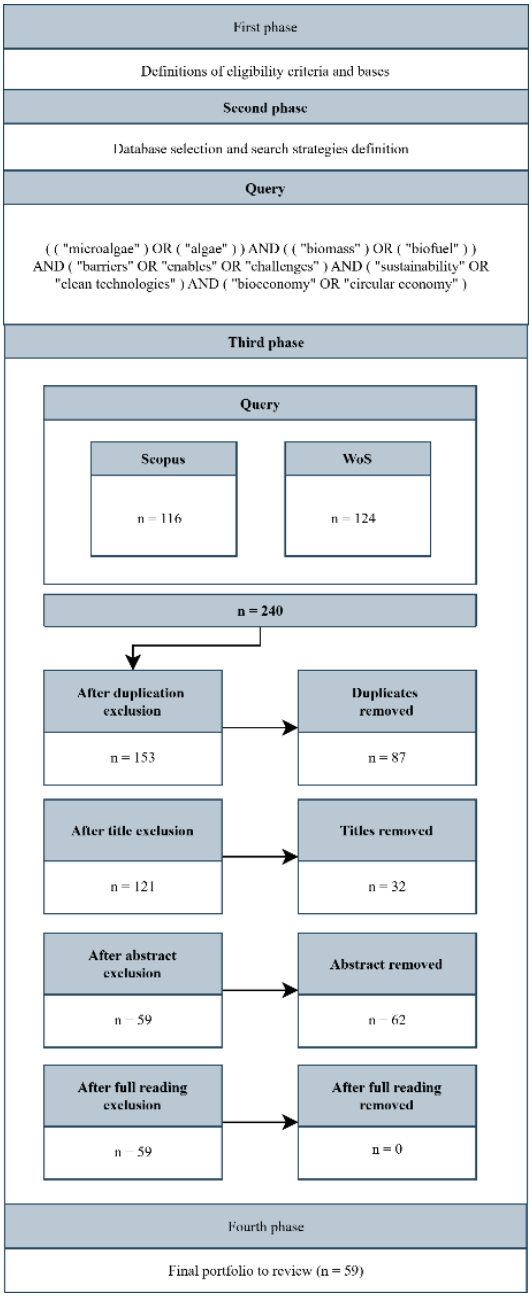
The overall sample was collected according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) methodology, summarized in Figure 1. The data extraction process consists of four main phases. During the first phase, eligibility criteria and databases are defined. One of the eligibility criteria is the importance of biofuels from the third generation onwards. First- and second-generation sources are important, but they were excluded because they do not fall within the scope of advanced biofuels. Another point that makes the study eligible is its focus on and relevance to sustainability in conjunction with

the circular bioeconomy. Articles and reviews were considered eligible, excluding book chapters and conference papers.

The second phase is mainly characterized by the selection of databases and the definition of research strategies. The Scopus and Web of Science databases were considered, and only one query was defined: ((“microalgae”) OR (“algae”)) AND ((“biomass”) OR (“biofuel” OR “enables” OR “challenges”) AND (“sustainability” OR “clean technologies”) AND (“bioeconomy” OR “circular economy”). This query enables the achievement of the primary objective, which is to identify the challenges and propose a market strategy for advanced biofuels derived from microalgae.

During the third phase, the data filtering process takes place. From the overall sample of 240 articles, 87 were removed after reading the title, and 62 studies were removed after reading the abstract. No studies were removed after full reading, resulting in a total of 59 articles for the final review portfolio, considering the defined eligibility criteria.

**Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA).**



The fourth phase involved analyzing the metadata of the final 59 articles in the portfolio. During this process, using Biblioshiny on R-Studio, the Bradford Law was applied to confirm the core sources and the relevance of the study. Additionally, a thematic map was used to identify the maturity of the research concepts and the direction of innovation for the theme.

The primary goal of that analysis was to map out the scientific landscape of research on advanced biofuels derived from microalgae, thereby establishing the context for discussing barriers and enablers to market adoption. Afterward, it aimed to create a roadmap that synthesizes and connects the barriers and enablers identified in the systematic literature review

## 3. Results and Discussion

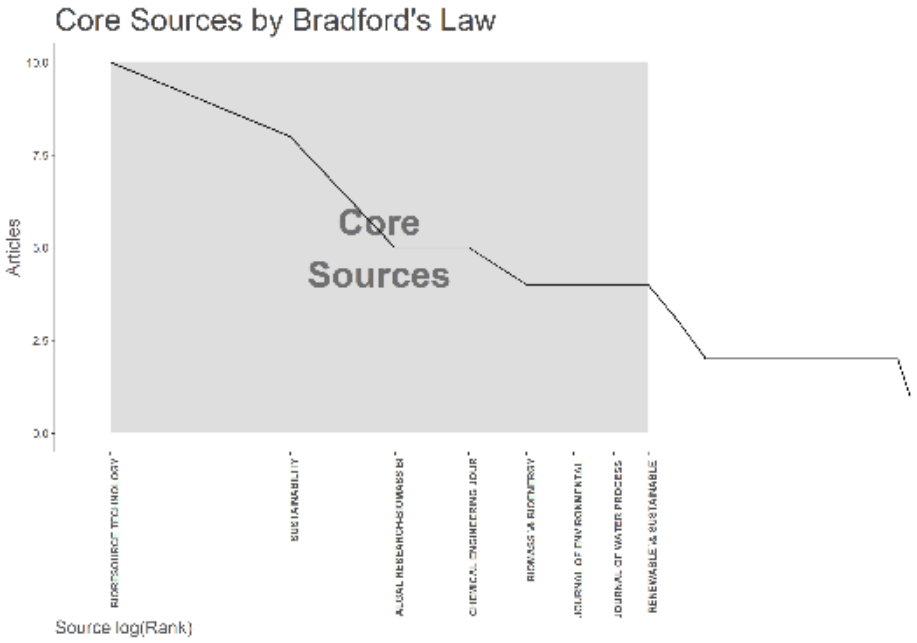
The systematic review process, which resulted in a final portfolio of 59 articles, allows us to outline the scientific landscape of research on advanced microalgae biofuels, establishing the context for discussing market barriers and strategies.

Despite the potential for energy transition from microalgae biofuels, the analysis shows that its market consolidation is inhibited by a set of interconnected barriers: (i) technological and process barriers; (ii) economic barriers; (iii) regulatory and market barriers. Given these three pillars, which impede the evolution and viability of the microalgae market, current research suggests that the field is moving away from a fragmented, disconnected approach and is recognizing that, for the microalgae market to succeed, all three pillars need to be integrated into a circular bioeconomy.

### 3.1. Bibliometric Analysis and Research Evolution

Scientific production in this area has shown accelerated and constant growth, especially since 2021, which justifies the relevance and strategic market opportunity addressed in this study. The analysis of the sources (Bradford's Law) confirmed that the portfolio was built from highly relevant sources (Figure 2), which ensures the robustness of the theoretical basis for the market and regulatory proposals.

**Figure 2. Bradford's Law for analysis of the sources.**



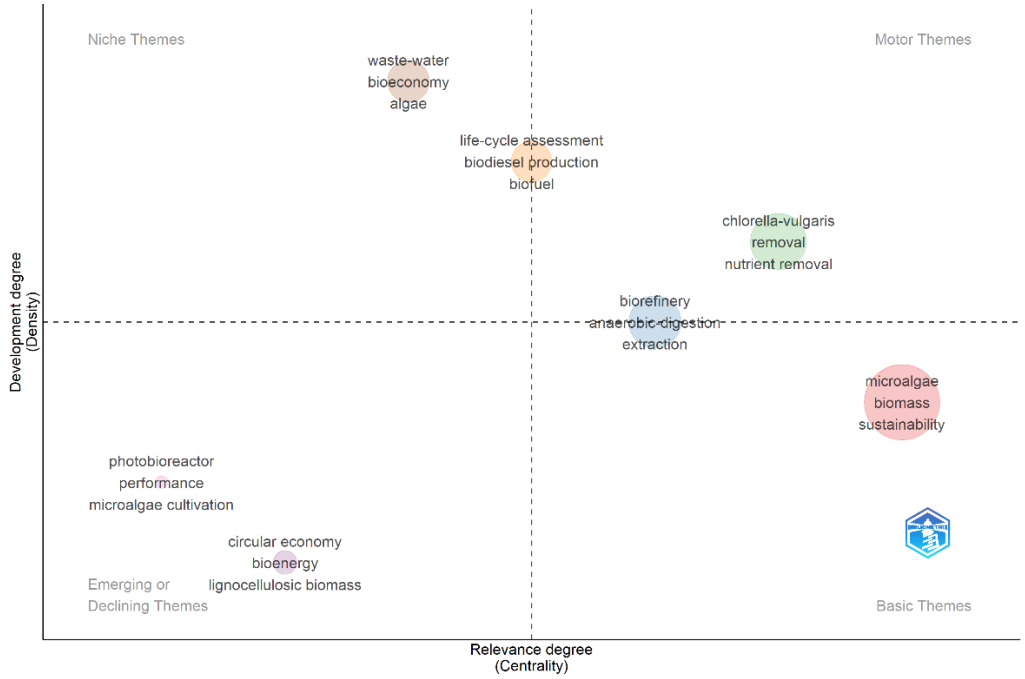
### 3.2. Strategic Focus and Areas of Convergence

The thematic map (Figure 3) reveals the maturity of research concepts and the direction of innovation in the field.

Basic themes: the concepts of microalgae, biomass, and sustainability form the core of the research, indicating that the sustainable potential of microalgae is already a consolidated pillar of the field.

Motor themes: concepts such as biorefinery, anaerobic digestion, and nutrient removal by Chlorella vulgaris emerge as themes of great relevance (centrality) and potential development (density). It confirms the paradigm shift from an isolated focus on biofuels to an approach of integral biomass valorization (biorefinery). Emerging themes, including the circular economy and bioenergy from lignocellulosic biomass, are rising themes that indicate future lines of research to optimize the process and diversify the raw material. The temporal evolution of Trend Topics reinforces this convergence, demonstrating the growing importance of terms such as biorefinery and circular economy from 2022 onwards.

**Figure 3. Thematic Map with research concepts.**




### 3.3. Technological Barriers

According to Goswami, Agrawal and Verma (2022), the primary technological barrier to market consolidation is the challenge of scaling production from the laboratory level to commercial scale, as well as the high risk of contamination in open systems. To overcome this situation, Gupta et al. (2025) conducted greenhouse experiments, established methodological pathways, transformed an extremophile alga, and achieved high yields, even under nutritional stress, for large-scale biodiesel production. The pathway facilitates the development of technologies in biogenetic engineering and also the evolution of large-scale production, directly impacting the economic viability of the sector.

### 3.4. Economic Barriers

In agreement with Solis et al. (2024), non-renewable fossil fuels may be cheaper to process. However, with a high environmental impact, the primary strategy to reduce production costs and increase profitability is the biorefinery and wastewater reuse approach, which integrates various processes capable of producing different bioproducts from microalgae biomass.

Biorefinery systems improve economic viability, also attesting to the importance of the circular bioeconomy approach, using wastewater along with microalgae cultivation for the production of advanced biofuels (Moreira et al., 2023). Due to the high cost of water and inorganic nutrients used in biofuel production, bioremediation with microalgae is a promising approach (Patel; Choi; Sim, 2020). While investigating, Goswami, Agrawal and Verma (2022) also found that the potential significance of using wastewater for biomass production with microalgae was identified, which can completely remove some nutrients from these waters, primarily the essential inorganic nutrients required for microalgae growth, such as nitrogen and phosphorus.

A central finding emerging from the literature is that focusing exclusively on the production of biofuels from microalgae results in a loss of investment in the market due to high production costs and wasteful biomass. Therefore, economic viability lies in a circular bioeconomy approach combined with biorefineries, generating a diversity of bioproducts, both high and low-value-added, thus improving the return on investment. The lack of consensus on third-generation biofuels and the absence of clear data on the market value of derived bioproducts also contribute to financial uncertainty in the market. Thus, another strategy is the need to integrate techniques such as LCA (Life Cycle Assessment) and LCC (Life Cycle Cost) to justify the environmental and commercial viability of understanding the value chain of bioproducts derived from microalgae (Préat et al., 2020).

### 3.5. Market and Regulatory Barriers

The absence of supportive public policies is a fundamental regulatory barrier. The literature emphasizes the importance of continually reviewing and improving diverse policy guidelines to promote the growth of the biofuel and bioproduct market derived from microalgae, as well as ongoing investment in research and development to address the aforementioned technological inefficiencies.

The literature review reveals some comprehensive approaches to the consensus on public policy needs, mentioned as key policy insights, among which the main ones are: standardization of renewable fuels; import and export policies; investment in research and infrastructure, which can be a direct facilitator to overcome the limitations of large-scale productivity and high production costs; education and public engagement (Kant et al., 2025).

Therefore, why is educating the population so important? According to Ubando et al. (2022), Chen et al (2022) and Rosero-Chasoy et al (2021), engaging the population and fostering a culture of development in a circular bioeconomy can be crucial for creating value and addressing the need for biofuels and other third-generation bioproducts.

### 3.6. Strategic Roadmapping: from barrier to biorefinery as a Blue Ocean

As demonstrated in the analysis and the consolidation of barriers, overcoming technological and economic challenges requires a systemic solution based on process integration. The viability of the advanced microalgae biofuel market lies in adopting a biorefinery approach, combined with the Blue Ocean Strategy, which shifts the focus from a low-value product (pure biofuel) to a diversified, high-value-added product portfolio.

To guide this transition, a four-pillar strategic roadmap is proposed (Figure 4), which links R&D, regulatory, and market actions, as illustrated in Figure 4.

The first pillar focuses on overcoming large-scale productivity barriers and the high risk of contamination in open systems. Advancement in cultivation systems in continuous investment in research and development (R&D) to optimize photobioreactor and hybrid cultivation systems in order to increase precision and biomass. Biogenetic engineering of microalgae focuses on the cultivation of extremophilic or genetically modified microalgae, which exhibit high yield even under nutritional stress, facilitating large-scale biodiesel

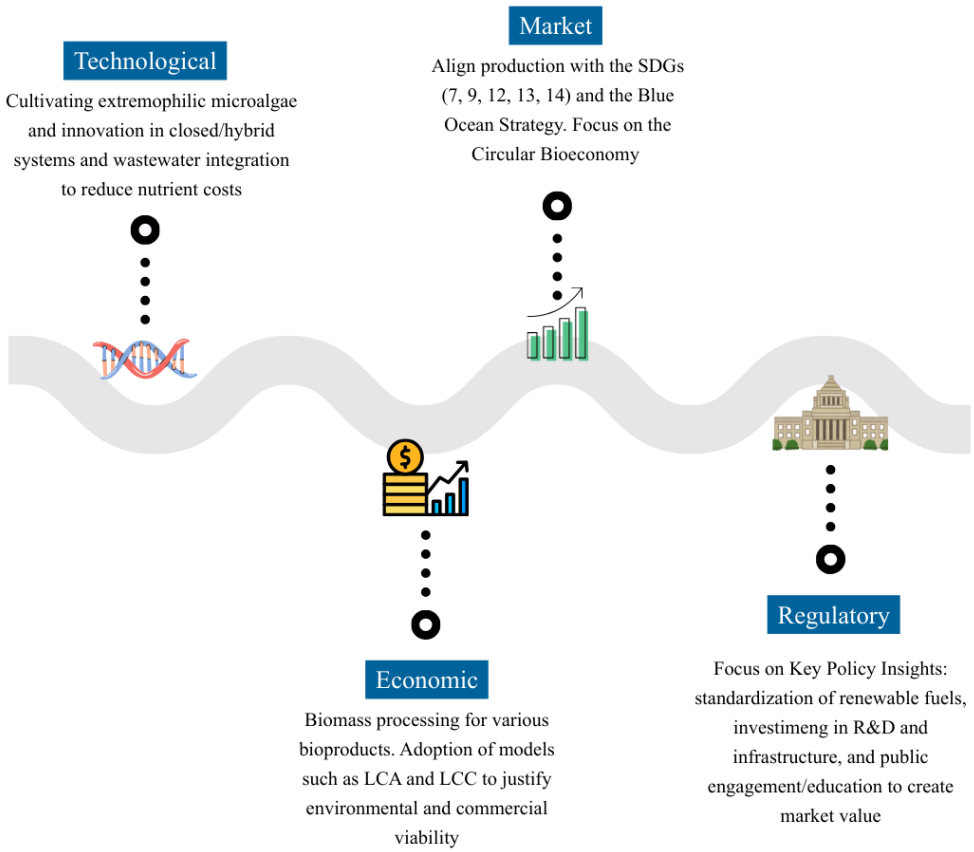
production and improving economic viability. Innovations in processing focus in optimization of low-cost extraction and flocculation techniques.

The second pillar addresses the high cost of production and energy investment, transforming waste into profit, using the concept of a circular bioeconomy. The biorefinery and circularity approach integrates processes capable of producing various bioproducts, including pharmaceuticals, cosmetics, food, and biofuels, from microalgae biomass. The use of microalgae in the bioremediation of wastewater to meet the demand for primary nutrients (nitrogen and phosphorus) significantly reduces production costs while promoting the circularity of the wastewater. Application of analyses such as LCA (Life Cycle Assessment) and LCC (Life Cycle Cost) to justify environmental and commercial viability and provide clear data on the market value of the derived products.

The third pillar is crucial for mitigating regulatory and market barriers, requiring the intervention of policymakers. R&D incentive policies to direct government support for investment in research and infrastructure to overcome technological inefficiencies and high initial costs. Additionally, focus on policies that promote the circular economy and the biorefinery approach as a standard industry practice. In this way, key policy insights are a primary need for the standardization of renewable biofuels and clear import/export guidelines to provide security and consensus to the market

The final pillar focuses on building value for third-generation biofuels, overcoming the lack of consensus and financial uncertainty, and aligning with global agendas to strategically position the sector based on the SDG goals, thereby attracting investors aligned with sustainability.

**Figure 4. Four-pillar strategic roadmap.**




## 4. Conclusion

In conclusion, this study addressed the viability of the advanced biofuels market derived from microalgae from a sustainable perspective. Based on the analysis and discussion of the literature, the consolidation of the advanced biofuels market depends on a set of barriers: technological, economic, and regulatory. It is also demonstrated that the sustainable and market efficiency of the sector requires a more fragmented approach, defining that the challenges should be addressed jointly and systemically.

In light of this, the research highlights that focusing primarily on the production of biofuels from microalgae is economically unfeasible, as it results in high energy costs for lipid extraction and refining, ultimately wasting biomass during the process. Economic viability, according to most studies, depends on the concept of biorefinery within the circular bioeconomy model. Integrating cultivation with waste circularity maximizes returns and also generates other bioproducts from the same biomass.

Regardless of technological and economic advancements, public relations should function as a support system, requiring public policies that encourage research and development in the field, engaging in public education to build a culture of circularity, and creating the necessary demand to consolidate sustainable products.

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