Available online on: http://ejournal.undip.ac.id/index.php/teknik

TEKNIK, 46 (1), 2025, 57-72

The Role of Algae in Biofuel Production: Potentials and Challenges for Sustainable Transportation

Dessy Agustina Sari[1,2], Moh. Djaeni[1*], Hadiyanto[1], Aji Prasetyaningrum[1]

[1] Department of Chemical Engineering, Faculty of Engineering, Universitas Diponegoro, Jalan Prof. Soedarto, S.H., Tembalang, Semarang – Jawa Tengah, Indonesia, 50275
[2] Chemical Engineering Program, Faculty of Engineering, Universitas Singaperbangsa Karawang Jalan HS Ronggowaluyo Telukjambe Timur Puseurjaya, Karawang – Jawa Barat, Indonesia, 41361

Abstract

This study aims to explore the potential of algae for sustainable biofuel production by examining their molecular biology and the use of advanced cultivation techniques. As concerns over greenhouse gas emissions and rising transportation energy costs grow, algae offer a promising alternative for fuel derived from food and non-food sources. This review examines the main biological pathways involved in making biofuels from algae. It focuses on species diversity, lipid content, and new technologies like photobioreactors and magnetic nanoparticle harvesting. The results showcase noteworthy advancements in biotechnology and genetic engineering that boost algae productivity and fuel yield while also critically examining the environmental impacts, such as CO_2 emissions and water use, and the economic and policy challenges through a life cycle analysis. Adopting a global perspective, this review emphasizes the role of international collaboration and technology transfer in overcoming barriers. Conclusion: Algae-based biofuels have considerable potential for reducing CO_2 and supporting sustainable transportation, yet scaling up production and lowering costs remain challenging. Future research should focus on improving integrated biorefinery platforms, exploring CO_2 capture, and promoting international partnerships.

Keywords: *algae biofuel; bioenergy policy; carbon sequestration; energy transition; genetic engineering*

1. Introduction

Fossil fuels still take up most of the global energy scene, accounting for about 80% of all energy used on Earth (Cheah et al., 2020; Williams, 2013). In particular, this dependence on fossil fuels has led to substantial environmental problems—greenhouse gas emissions and climate. The burning of fossil fuels produces significant volumes of carbon dioxide (CO_2) and other pollutants, including nitrogen oxides (NO_x) and sulfur oxides (SO_x), therefore aggravating the climate problem and worsening air quality. With about 60% of world energy consumed in metropolitan areas, the International Energy Agency (IEA) notes that these places are significant sources of human CO_2 emissions (Williams, 2013).

Driven by population increase and economic development, especially in nations like India and China, projections show that world energy consumption will rise by almost 50% by 2035 (Villarante & Ibarrientos, 2021). This situation calls for a critical review of energy policy and methods to minimize the negative consequences of depending too much on fossil fuels. While switching to renewable energy sources is necessary, it is also important to recognize upfront the financial difficulties related to these substitutes, mainly algae biofuels. Notwithstanding their environmental benefits, the high production costs and existing technological constraints are significant obstacles to the general use of algal biofuels (Hannon et al., 2010; Villarreal et al., 2020).

In terms of greenhouse gas emissions especially, sustainable transportation is any movement that has minimal effect on the surroundings. Comprising about a quarter of world energy consumption and associated emissions, the transportation industry mainly contributes to global carbon emissions (Batur et al., 2019). The demand for sustainable transportation solutions grows more urgent as urbanization and economic activities keep rising to help to minimize the adverse environmental effects connected with conventional transportation systems (Mo & Wang, 2019).

The promotion of sustainable transportation depends much on technological developments. One limiting element is the typically significant financial outlays required to deploy these technologies. For

*) Corresponding Author.
E-mail: moh.djaeni@live.undip.ac.id

doi: 10.14710/teknik.v46i1.67532

example, even if electric cars (EVs) present a good substitute for traditional cars, the infrastructure expenses related to general EV adoption remain a significant obstacle (Chapman, 2007). Balancing economic development with the necessity to lower transportation-related carbon emissions depends on integrating clean energy technologies (Tang et al., 2023). Significant decreases in transportation-induced carbon emissions could result from more investments in renewable energy sources (Anwar et al., 2021).

Biofuels, especially those made from algae, have attracted much interest as workable substitutes for fossil fuels in the transportation industry. Third-generation biofuels, algae, offer unique benefits over conventional biofuels because of their fast rates of growth, low land needs, and capacity to generate high lipid content fit for fuel manufacture. Without conflicting with agricultural land or affecting food supply, some algae species can have up to 40% fatty acids, which can be transformed into biodiesel and ethanol (Chang et al., 2013; Rösch et al., 2018). Notwithstanding these encouraging features, significant obstacles still stand in the way of the economic viability and mass manufacturing of algae biofuels. Algal biofuels' competitiveness against fossil fuels and other biofuel sources is hampered by the sometimes complicated and expensive current production technologies (Adeniyi et al., 2018; Pankratz et al., 2019).

Although algae biofuels have great potential as sustainable energy sources, present research gaps must be filled. First, there is little thorough research combining the pragmatic difficulties of mass biofuel generation with

Table 1. Comparison of biofuels: algae vs. first and second-generation biofuels

No	Parameter	Algae Biofuels (Third-Generation)[a]	First-Generation Biofuels[b]	Second-Generation Biofuels[c]
1	Feedstock	Microalgae, macroalgae	Food crops (e.g., corn, sugarcane)	Non-food biomass (e.g., waste, lignocellulose)
2	Lipid content	20-50% of dry weight	1-5% of dry weight	10-20% of dry weight
3	Growth rate	Rapid (days)	Moderate (months)	Slow to moderate (weeks to months)
4	Land use	Non-arable land, marginal land	Requires arable land	Marginal or degraded land
5	Water use	Can use saline or wastewater	Requires freshwater	Varies; generally lower than first-gen biofuels
6	CO_2 sequestration potential	High (potential for carbon neutrality)	Low	Moderate
7	Yield (L/ha/year)	20,000 - 60,000	500 - 6,000	1,000 - 15,000
8	Environmental impact	Low (no food competition)	High (food competition, significant land use)	Moderate
9	Technology maturity	Emerging technology	Established technology	Developing technology

[(1,3,5,7,9)a](Rösch et al., 2018); [(1,3,5,7,9)b](Bai et al., 2016); [(1,3,5,7,9)c](Demırbas, 2011); [(2,3,4,6,8)a](Chang et al., 2013); [(2,4,6,8)b](Adeniyi et al., 2018); and [(2,4,6,8)c](Pankratz et al., 2019).

Table 2. Lipid content and biofuel potential of selected algae species

No	Algae Species	Lipid Content (% dry weight)	Primary Biofuel Product	Special Characteristics
1	*Chlorella vulgaris*	28-32	Biodiesel	Rapid growth, adaptable to various conditions
2	*Nannochloropsis oculata*	30-50	Biodiesel	High lipid content, robust growth in diverse conditions
3	*Spirulina platensis*	4-9	Biogas	High protein content, widely used as a dietary supplement
4	*Botryococcus braunii*	25-75	Hydrocarbon fuels	Produces long-chain hydrocarbons, suitable for fossil fuel alternatives
5	*Dunaliella salina*	20-30	Biodiesel	Thrives in high salinity environments, lipid accumulation under stress

[1](Griffiths & Harrison, 2009; Khan & Shin, 2018); [2](Andriopoulos & Kornaros, 2023; Blockx et al., 2018; Minhas et al., 2023; Sung et al., 2018); [3](Jamilatun et al., 2020; Mussgnug et al., 2010; Yilancioglu et al., 2016); [4](Hu et al., 2008; Spolaore et al., 2006); and [5](Griffiths & Harrison, 2009; Khan & Shin, 2018).

doi: 10.14710/teknik.v46i1.67532

Table 3. Summary of algae biomass conversion processes

No	Conversion Process	Primary Biofuel Output	Advantages	Challenges
1	Transesterification	Biodiesel	High efficiency, well-established	Requires purified lipids, generates glycerol
2	Pyrolysis	Bio-oil	Converts whole biomass, versatile product	Requires high temperatures, complex refining
3	Gasification	Syngas	Can utilize wet biomass, flexible end products	High energy input, complex technology
4	Anaerobic digestion	Biogas	Produces energy and organic fertilizer	Slower process, limited to organic materials

[1](Rawat et al., 2013); [2](Radakovits et al., 2010); [3](Slade & Bauen, 2013); and [4](Clarens et al., 2010).

the most recent biotechnology innovations in algae farming. Furthermore, understudied are the long-term environmental effects of increasing algae biofuel production, especially carbon sequestration and resource use efficiency. Furthermore, lacking in research is the integration of algal biofuels into current transportation energy systems, particularly about policy frameworks and economic viability.

With an emphasis on the most recent biotechnological developments and their capacity to overcome current obstacles, this review seeks to close these gaps by offering a thorough study of the present situation of algal biofuel generation. This work is unique in synthesizing current developments in algae growing and biofuel conversion technology together with a thorough analysis of the sustainability of algal biofuels. This analysis provides fresh insights into the feasibility of algal biofuels as a pillar of sustainable transportation by combining ideas from several domains, supporting the larger conversation on renewable energy transitions. **Table 1** compares key parameters between algae biofuels and first- and second-generation biofuels, highlighting the advantages of algae in terms of environmental impact, land use, and CO_2 sequestration.

2. Materials and Methods

2.1. Literature Search Strategy

Focusing on the part algae will play in biofuel generation from 2003 to 2024; this part describes the method utilized to compile and evaluate pertinent research for this review. Databases used. Reputable academic databases, including PubMed, Scopus, Web of Science, and Google Scholar, were searched in the literature. These databases were chosen for their thorough coverage of scientific papers and their applicability to biotechnological developments, environmental research, and biofuels. Key search terms included algae biofuel production, sustainable transportation, biotechnological advancements in algae, environmental impact of algae biofuels, carbon sequestration by algae, economic feasibility of algae biofuels. These terms were combined with Boolean operators (AND, OR) to refine the search results and focus on studies relevant to the scope of this review.

Inclusion criteria: articles published between 2003 and 2024; peer-reviewed articles focusing on algae biofuels, sustainable transportation, and related biotechnological advancements; and studies providing quantitative or qualitative data on algae biofuel

Table 4. Challenges in scaling up algae biofuel production and potential solutions

No	Challenge	Impact on Production	Potential Solutions
1	Maintaining high yields in large-scale operations	Inconsistent biomass and lipid yields	Development of robust algae strains; optimized cultivation systems
2	Impact of environmental factors on lipid content	Reduced lipid accumulation and biofuel yield	Controlled environmental conditions; use of stress-tolerant strains
3	Economic feasibility	High production costs, limiting commercial viability	Technological advancements; cost-reduction strategies

[1](Chisti, 2007; Zhou et al., 2011); [2](Griffiths & Harrison, 2009; Grobbelaar, 2009); and [3](Craggs et al., 2011; Morales et al., 2019).

doi: 10.14710/teknik.v46i1.67532

production, environmental impacts, and economic considerations. Then, exclusion criteria include articles focusing exclusively on non-algae biofuels and studies with insufficient methodological detail or those published in non-peer-reviewed sources.

First, the titles and abstracts of the obtained papers were screened for relevance. Reviewing full-text articles helped to guarantee that the references fit the inclusion criteria. Studies that did not directly support the goals of the review were deleted, as well as duplicates—literature search flow diagram. The literature search and selection procedure was recorded using a PRISMA flow diagram (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), improving openness. The number of studies found, screened, evaluated for eligibility, and added to the review is shown here.

2.2. Data Extraction and Analysis

The review focuses on extracting and synthesizing data related to biological data, information on algae species used for biofuel production, including growth rates, lipid content, and environmental conditions. Technological advancements are innovations in algae cultivation and biofuel conversion processes. Environmental impact metrics are data on carbon sequestration potential, water use efficiency, and land use. Economic analysis are information on production costs, cost-benefit analyses, and market trends. To guarantee uniformity and correctness, data were taken from a standard form. Using the themes of biological features, technical innovations, environmental implications, and economic feasibility. **Figure 1** is the method included for grouping the data. The quality of the studies included in this review was assessed using specific criteria, such as methodological rigor: evaluation of study design, sample size, and statistical analyses. Relevance is alignment with the review's objectives, focusing on the practical application of findings. Transparency is availability of detailed methodologies and data. Based on these criteria, studies were ranked as high, medium, or low, ensuring that only reliable and relevant studies were included in the review.

Although the search approach was meant to be all-encompassing, certain biases might affect the results or reading of this review. These include database constraints since the review was primarily based on studies indexed in particular academic databases and language restrictions since only papers written in English were regarded. These prejudices can cause pertinent papers published in other languages or less-accessible publications to be excluded, therefore basing the review results. The consequences of these prejudices are clear-cut. Hence, efforts were taken to minimize their influence by presenting a broad spectrum of studies from many fields and areas.

2.3. Review Structure and Organization

The review is organized around key themes that emerged from the literature, including biological aspects: species diversity, growth conditions, and lipid content of algae. Biotechnological advances: Innovations in genetic engineering, cultivation systems, and conversion technologies. Environmental impact: carbon sequestration, water use, and land impact assessments.

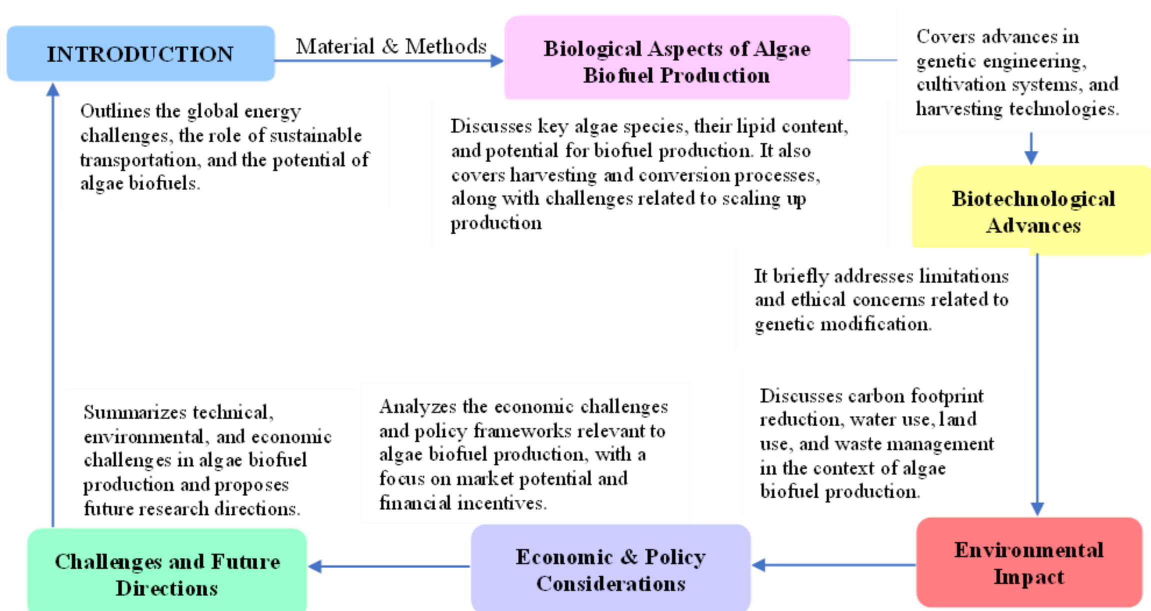

Figure 1. Main point of each chapter in the manuscript

doi: 10.14710/teknik.v46i1.67532

Economic feasibility: analysis of production costs, market trends, and policy frameworks supporting algae biofuels.

When pertinent, the review contrasts several studies with an eye toward changes in methodology, results, and future implications of these variances for the generation of algae biofuel. For instance, studies employing various algae species or growing methods are examined to determine how they affect lipid content and general biofuel yield.

2.4 Limitations of the Review

Focusing primarily on algae biofuels, this review spans papers released between 2003 and 2024. Although the review seeks to offer a thorough study of the subject, it does not particularly explore the whole range of renewable energy technologies or biofuels produced from different sources. The emphasis on a particular timeline and biofuel source could overlook relevant information from past research or other renewable energy sources, offering a more extensive background or other viewpoints. As said, the choice of studies could lead to possible biases, primarily if pertinent research was published in less readily available publications or outside the chosen period. These prejudices can affect the generalizability of the results since the absence of non-English research or those not indexed in the chosen databases might lead to a limited field of view. This restriction is acknowledged, so future studies should include a broader spectrum of sources to offer a more complete grasp of the issue.

Future studies should concentrate on long-term environmental consequences, the scalability of algae biofuel generation, and the integration of algae biofuels into current energy systems depending on the gaps found. Furthermore, more studies are required to maximize the financial feasibility of algal biofuels through biotechnological developments and regulatory support. Investigating multidisciplinary approaches combining knowledge from past studies, grey literature, and newly developing renewable energy sources could also provide a more complete picture of the difficulties and possibilities in algal biofuel production.

3. Result and Discussion

3.1. Biological Aspects of Algae Biofuel Production

3.1.1. Algae species and their potential for biofuel production

Diversity of algae species. From unicellular microalgae to multicellular macroalgae, algae constitute various photosynthetic organisms. Their fast development and high lipid content qualify them as perfect candidates for biofuel generation. *Chlorella vulgaris*, *Nannochloropsis oculata*, *Spirulina platensis*, *Botryococcus braunii*, *Tetraselmis chuii*, and *Dunaliella salina* are important species showing great promise. High lipid accumulation of these species makes them desirable; transesterification techniques allow their conversion into biodiesel (Griffiths & Harrison, 2009; Khan & Shin, 2018).

Algal lipid concentration differs significantly between species, usually ranging from 20 to 50% of their dry weight. The quality and quantity of the biofuel depend on the makeup of these lipids, so it is crucial. For instance, *Botryococcus braunii* is well-known for its high hydrocarbon concentration, which may be straight-forwardly turned into fuels without any processing (Spolaore et al., 2006). The stability and combustion characteristics of the resultant biodiesel are influenced by algae's fatty acid profile, especially about saturated and monounsaturated fatty acids (Hu et al., 2008).

Many environmental elements affect algae growth: light intensity, temperature, pH, and nutrition availability. Although species have different optimal growth circumstances, generally, algae need lots of sunlight, a steady temperature range (20–30°C), and a balanced supply of nutrients, including nitrogen, phosphorous, and trace metals (Singh & Gu, 2010). Recent research on using wastewater as a food source for algae production supports development and helps wastewater treatment by eliminating pollutants (Cai et al., 2013). **Table 2** below summarizes the lipid content, primary biofuel products, and special characteristics of these algae species

3.1.2 Harvesting and biomass conversion processes

Harvesting algae efficiently is a critical step in biofuel production. Standard methods include centrifugation, flocculation, filtration, and sedimentation. Each method has its advantages and challenges, centrifugation is effective but energy-intensive, making it costly for large-scale operations. Flocculation involves adding chemicals to aggregate algal cells, making separating them from the growth medium easier. However, using chemicals can introduce contaminants that need to be removed during biofuel production. Filtration and sedimentation are more cost-effective but may be less efficient, particularly for microalgae with small cell sizes (Uduman et al., 2010).

Algal biomass can be transformed into biofuel using numerous techniques, including transesterification, pyrolyzed, gasification, and anaerobic digestion once harvested, transesterification is the most common method for producing biodiesel, where lipids are reacted with alcohol (usually methanol) in the presence of a catalyst to produce fatty acid methyl esters (FAME) and glycerol. Pyrolysis involves the thermal decomposition of biomass in the absence of oxygen, producing bio-oil, which can be further refined into biofuels. Gasification converts biomass into syngas (a mixture of hydrogen and carbon monoxide), which can be used to produce synthetic fuels. Anaerobic digestion breaks down organic matter without

doi: 10.14710/teknik.v46i1.67532

oxygen, producing biogas (mainly methane), which can be used for energy production (Rawat et al., 2013). **Table 3** summarizes, together with their benefits and drawbacks, the primary conversion techniques for converting algal biomass into biofuels.

3.1.3 Factors affecting algal biofuel production

The availability of nutrients strongly influences algal development and lipid buildup. For many algal species, nitrogen limitation is well-known to increase lipid accumulation since the organisms change their metabolism toward energy storage (lipid formation) rather than development (Griffiths & Harrison, 2009). Still, a balance has to be kept since too few nutrients might reduce general biomass output.

Algal photosynthesis and growth rates are highly influenced by light intensity and quality. Usually needing particular light wavelengths for best development, algae find blue and red light most beneficial. Temperature is also important; most algae grow between 20 and 30°C. Deviations from this range might slow down or harm the cells (Grobbelaar, 2009; Sari et al., 2018).

Photosynthesis depends on CO_2, which concentration in the growing environment might affect algal development. Though the ideal concentration differs between species, studies have indicated that raising CO_2 levels can boost biomass output (Chinnasamy et al., 2014). Furthermore, suggested as a means to lower greenhouse gas emissions and generate biofuel is employing industrial CO_2 emissions as a carbon source for algae growth (Ho et al., 2011).

3.1.4 Challenges in scaling up algae biofuel production

Maintaining good yields in large-scale operations presents one of the most important obstacles in increasing algal biofuel output. The complexity of controlling environmental parameters, including light, temperature, and nutrition availability, rises along with the size of the output. Variations in these elements might cause fluctuations in lipid content and general biomass yield, making it challenging to attain constant production at a commercial scale (Chisti, 2007; Zhou et al., 2011).

Environmental factors like temperature, light intensity, and nutrition availability directly influence the lipid content of algae. Maintaining ideal conditions becomes even more difficult in large-scale operations, which might lead to poorer biofuel yields and reduced lipid buildup. Changing temperatures, for instance, can stress algal cells and result in less-than-ideal lipid synthesis (Grobbelaar, 2009). Furthermore, nutrient availability has to be closely controlled to avoid excess or shortage, which might affect lipid accumulation (Griffiths & Harrison, 2009).

An important obstacle to commercialization still is algae biofuel's economic viability. Significant difficulties arise from the high expenses related to farming, harvesting, and processing and the energy-intensive character of these operations (Craggs et al., 2011). Technological developments are required to increase efficiency and lower the manufacturing of algal biofuel expenses. Higher lipid content, genetically modified algae strains, and more effective photobioreactors could help solve these issues (Morales et al., 2019). **Table 4** summarizes the key challenges in scaling up algae biofuel production and potential solutions, providing a clear overview of the obstacles and strategies for overcoming them.

3.2 Biotechnological Advances

3.2.1 Genetic engineering of algae

Genetic engineering in algae mainly aims to raise lipid content, directly affecting biodiesel yield. To improve lipid biosynthesis, researchers have effectively changed metabolic routes in several types of algae. For instance, it has been demonstrated that overexpression of the gene encoding acetyl-CoA carboxylase (ACCase), a fundamental enzyme in fatty acid production, increases lipid accumulation in *Chlorella species* (Ajjawi et al., 2017). Another strategy entails downregulating starch synthesis pathways, guiding carbon flow toward lipid synthesis rather than carbohydrates (Radakovits et al., 2010).

Furthermore, the improvement of algae's growth rates has been emphasized by genetic changes. Under different environmental conditions, researchers have created algal strains that develop faster and collect biomass more effectively by changing the expression of genes linked to photosynthesis and carbon fixation (Ruan et al., 2012). For example, *Chlamydomonas reinhardtii* has been modified to overexpress genes linked to light-harvesting complexes, so improving its photosynthetic efficiency and, hence, its growth rate (Mussgnug et al., 2007).

3.2.2 Innovative cultivation systems

Advanced cultivation techniques called photobioreactors maximize algae exposure to light, hence improving photosynthesis and biomass generation. Designed as closed systems, they guard algae against contamination and enable exact control over factors including temperature, light intensity, and CO_2 concentration (Carvalho et al., 2006). Using flat-panel and tubular systems, among other photobioreactor design innovations, has enhanced light distribution and gas exchange, increasing productivity relative to conventional open pond systems (Lehr & Posten, 2009).

Open ponds and photobioreactors have benefits together in hybrid farming systems. Usually starting in open ponds where algae are exposed to natural sunlight and ambient CO_2, these systems move to photobioreactors for the last biomass buildup under controlled circumstances (Chisti, 2007). Large-scale biofuel generation finds great promise in this method

doi: 10.14710/teknik.v46i1.67532

since it lowers the total cost of farming while preserving high biomass yields. **Table 5** lists the main biotechnological developments in the generation of algal biofuel, stressing important discoveries and related case studies or instances.

High-frequency sound waves used in ultrasonic treatment break cell barriers, improving intracellular lipid release (Sari et al., 2025). Combining this technology with additional extraction techniques—solvent extraction or supercritical CO_2—helps maximize algae lipid recovery (Lee et al., 2010). Ultrasonic aided extraction is especially successful for microorganisms with rigid cell walls, including *Nannochloropsis species*, which are otherwise difficult to handle.

3.2.3 Biotechnological challenges and future directions

Although laboratory-scale genetic engineering has dramatically expanded the possibilities for the generation of algae biofuel, scaling these technologies for commercial use faces apparent difficulties. Particularly under different climatic conditions faced in large-scale outdoor farming systems, one of the main issues is the durability of genetically modified features across several generations (Gressel, 2008). The other significant hurdles are political acceptability and legal disputes. Regionally, GMOs can have a tediously lengthy and complex approval process, given the stringency of rules in different places. Public perceptions of GMOs, particularly where strong anti-GMO attitudes prevail (Villarreal et al., 2020), may also affect the market's acceptability.

Additionally, gene manipulation in algae raises questions about potential environmental risks involving a series of ethical considerations. Proposals suggest that introducing genetically engineered algal cultures into natural environments may result in unintended consequences, such as contaminating nearby ecosystems or creating new invasive species (He et al., 2014). Concerns about food safety and global environmental impacts have driven public disapproval of GMOs, complicating the general acceptance of these technologies (Schnettler et al., 2010). A complete and comprehensive ecological risk analysis, along with open public and stakeholder communication, should reveal these issues.

However, numerous mechanical obstacles persist despite advancements in agricultural logging knowledge and data collection devices. For instance, the cost of building or operating photobioreactors, even when these options function effectively in a controlled e nvironment, prevents them from scaling up (Carvalho et al., 2006). Furthermore, while magnetic nanoparticles present a unique opportunity for harvesting in cascade concentration systems (Vandamme et al., 2012), the manufacturing cost and specialized equipment make them less appealing than alternatives. Continuous research and development will allow us to work through these constraints to realize the commercial viability of algal biofuels.

The identified key ethical, logistical, and technological dilemmas concerning algae biofuel production underline that future research efforts are to focus on developing practical, affordable solutions. Genetic engineering innovations, such as the creation of genetically modified strains capable of more stable functions (Carruthers et al., 2019), can potentially enhance the scalability and sustainability of algal biofuels. Moreover, research in the field of integrated systems that integrate waste treatment and carbon capture technologies with algae farming provides new opportunities to reduce environmental impact and cost.

3.3 Environmental Impact

3.3.1 Carbon footprint reduction

Algae biofuel production presents a viable route to drastically lower greenhouse gas (GHG) emissions than more conventional fossil fuels. As a carbon sink, algae are pretty effective in photosynthesis, taking CO_2 from the atmosphere or straight from industrial emissions. During their growth period, algae can absorb

Table 5. Summary of biotechnological advances, challenges, and solutions in algae biofuel production

Biotechnological Advance	Description	Case Study/Example
Genetic engineering[1]	Enhancing lipid content and growth rates through metabolic pathway manipulation	*Chlorella species* with increased lipid accumulation via overexpression of ACCase; *Chlamydomonas reinhardtii* engineered for faster growth
Photobioreactors[2]	Closed systems optimizing light and CO_2 for higher biomass production	Flat-panel and tubular photobioreactors improve productivity in comparison to open ponds
Hybrid cultivation systems[3]	Combining open ponds and photobioreactors for cost-effective, high-yield production	Initial growth in open ponds followed by final accumulation in photobioreactors

[1](Ajjawi et al., 2017; Mussgnug et al., 2007), [2](Carvalho et al., 2006; Lehr & Posten, 2009), and [3](Chisti, 2007).

doi: 10.14710/teknik.v46i1.67532

Table 6. Comparative environmental impacts of algae biofuels vs. conventional biofuels

No	Environmental Impact Category	Algae Biofuels	Conventional Biofuels (e.g., Corn Ethanol, Soy Biodiesel)
1	Carbon footprint	Low to negative carbon footprint due to CO_2 absorption during cultivation	High carbon footprint due to land-use change, fertilizer use, and lower CO_2 sequestration potential
2	Water use	High water use can be mitigated by using saline water or wastewater	High water use often requires freshwater for irrigation, leading to competition with food crops
3	Land use	Low land use; can be grown on non-arable land and in saline environments	High land use often competes with food production, leading to deforestation and habitat loss
4	Ecosystem impact	The potential risk of non-native species introduction and algal blooms can be mitigated with closed systems	Significant ecosystem disruption due to land conversion, pesticide, and fertilizer runoff
5	Nutrient use and recycling	Efficient nutrient use with potential for recycling, especially when using wastewater	High nutrient use, with significant runoff leading to waterway pollution and eutrophication
6	Waste management	Residual biomass can be used for co-products (e.g., biogas, fertilizer), reducing waste	Often generates significant agricultural Waste, with limited recycling of nutrients and byproducts
7	Energy efficiency (EROI)	Variable; can be improved with renewable energy integration and waste-to-energy systems	Generally, lower EROI, especially when considering energy inputs for cultivation and processing

[1](Ho et al., 2011; Mu et al., 2014); [2](Clarens et al., 2010; Rocha et al., 2021); [3](Chisti, 2007; Zhang et al., 2016); [4](Bettencourt et al., 2021; Clarens et al., 2010); [5](Craggs et al., 2011; Mancosu et al., 2015); [6](Leow et al., 2018; Zhang et al., 2016); and [7](Clarens et al., 2010; Sills et al., 2012)

significant volumes of CO_2, which they then convert into biomass. Particularly in cases of algae grown utilizing CO_2 recovered from flue gases generated by power plants or industrial sites, this technique can result in a net decrease in CO_2 level (Ho et al., 2011).

Algae-based biofuels have the potential to produce a low-carbon alternative, provided that the fuel is produced with renewable energy in the farming and processing stages (calculated using Life Cycle Assessment (LCA). For instance, cultivating algae in wastewater as fertilizer reduces the total energy input, and this synergy, along with co-benefits from wastewater treatment and biofuel production, contributes to even higher carbon savings (Mu et al., 2014). Nonetheless, reaching notable GHG reductions calls for maximizing several elements, including farming techniques, energy sources consumed, and biomass conversion efficiency. Although algae biofuels have great potential to reduce carbon emissions, their full environmental advantages depend on careful control of several elements.

3.3.2 Water use and resource management

Water utilization is a significant factor influencing the environmental impact of algal biofuel generation. Algae culture requires abundant water, particularly in open pond systems, a growth medium that evaporates readily. The choice of water resource, whether freshwater, saline, or even effluent, significantly influences the sustainability of the manufacturing process. While freshwater has potential added stress on local water supplies, saltwater or wastewater is a more sustainable alternative. In the context of global water scarcity (Bettencourt et al., 2021; Mancosu et al., 2015), it has become imperative to integrate wastewater management into the production cost and land use for algae-based biofuel production.

Growing algae on wasteland-like deserts is one method of industrial algae cultivation that has gained popularity over the years as a solution to water shortages. Algae thrive on non-arable land, making them ideal for saline environments where conventional farming methods are not feasible. Efficient use of brackish water or wastewater in arid regions could avoid displacing freshwater resources and provide a feedstock for the production of biofuels. This method alleviates water scarcity and the impact of producing biofuels on environmental sustainability through reduced demand for freshwater inputs (Rocha et al., 2021; Zhang et al., 2016).

doi: 10.14710/teknik.v46i1.67532

Production of algal biofuel depends on effective water resource management to be sustainable. Using closed-loop systems whereby water is recycled and repurposed throughout the manufacturing process can reduce freshwater needs. Photobioreactors and other water-efficient farming technologies help lower evaporation losses and enable more regulated water usage, supporting sustainable water management (Carvalho et al., 2006). Still, striking a balance between water use and output is somewhat tricky, especially in arid areas where water shortage is a genuine concern.

3.3.3 Land use and ecosystem impact

Compared to conventional biofuel crops like corn or soybeans, algal biofuel production has one significant benefit: its low land use. Where conventional farming is impossible, algae can be grown on non-arable ground—along coasts or in arid regions. This lessens the impact on food security and lessens competition for land with food crops (Chisti, 2007). Moreover, algae may be produced in saline water, lowering the demand for freshwater supplies and enabling farming in places unfit for other development.

Although there is little land use, extensive algae farming could affect nearby ecosystems, especially if non-native or genetically modified species are brought into natural surroundings. Another environmental issue is the possibility of algae blooms, which might exhaust oxygen in water bodies and damage aquatic life. Strong management policies and legal systems that track and control the environmental impact of algae growth help to reduce these hazards. Furthermore, using closed systems such as photobioreactors helps to stop the accidental release of algae into natural environments, safeguarding local biodiversity (Stephenson et al., 2010). **Table 6** below highlights important variations in sustainability across several impact categories by comparing the environmental effects of algae biofuels against conventional biofuels.

3.3.4 Waste and byproduct management

Reducing the environmental impact of the generation of algal biofuel depends critically on the effective utilization and recycling of nutrients. For development, algae need large doses of nutrients—mainly nitrogen and phosphorous. Using livestock manure for growing algae is another form of bio-fertilization practice that can provide significant nutrient inputs into systems (Craggs et al., 2011). Additionally, incorporating nutrient recycling methods within the production system, which involve salvaging and reusing nutrients from algal biomass, can enhance sustainability by reducing waste output and lowering the demand for external inputs.

Management of byproduct generation and leftover biomass after lipid extraction during algal biofuel production also affects the environmental footprint. Other bioenergy projects like anaerobic digestion and biogas generation could benefit from this residual biomass or serve as a nutrient-rich fertilizer for agricultural use (Leow et al., 2018). These integrated biorefinery systems utilize all the algal biomass, closing the waste cycle and transforming environmental liabilities into potential co-products.

3.3.5 Energy efficiency and lifecycle impacts

Energy return on investment (EROI) often measures the sustainability of biofuels, whether algae-based or not. It displays the produce-to-cost ratio of production value. If the EROI of algae biofuels remains unchanged, the researchers cannot consider it a sustainable fuel source. However, the current EROI for algae biofuels depends heavily on production costs and methods. Systems that use waste-to-energy systems for rooting and cutting, or those that farm the harvest using renewable energy, typically yield higher EROI (Sills et al., 2012). The energy efficiency of algae growth and processing can increase the latter's sustainability as a source of algal biofuels.

LCA provides a comprehensive picture of the environmental impacts of algae biofuel development, from production to end-use. The code guarantees the measurement of water extraction, Waste generated during production processes, greenhouse gas emissions, and energy sources used. LCA studies have demonstrated that algal biofuels, such as the one mentioned, significantly reduce greenhouse gases compared to fossil fuels, especially when combined with renewable sources during manufacturing and algae cultivation using wastewater (Mu et al., 2014). However, to fully realize these benefits and ensure that algal biofuels are a sustainable

Table 7. Cost-benefit analysis of algae biofuel production

No	Aspect	Costs	Benefits
1	Cultivation	High energy input, nutrient costs	High biomass yield potential
2	Harvesting	Expensive, energy-intensive	High lipid content
3	Conversion	Costly, requires advanced tech	Diverse biofuel products
4	Environmental impact	Water use, nutrient runoff	Carbon sequestration, low land use
5	Economic viability	High upfront investment	Potential for co-product revenue

[1,2](Morales et al., 2019); [3](Hannon et al., 2010); [4](Craggs et al., 2011); and [5](Patel et al., 2012)

doi: 10.14710/teknik.v46i1.67532

replacement for fossil fuels, ongoing productivity enhancements and continued attention to fertilizer needs and energy balances will be necessary.

3.4 Economic and Policy Considerations

3.4.1 Cost-benefit analysis of algae biofuel production

Primarily due to the energy-intensive operations in farming, harvesting, and biomass conversion into fuel, the manufacture of algal biofuels is linked with significant expenses. Important cost drivers are charges connected to fertilizer supplies, capital investments needed for photobioreactors or open pond systems, and energy costs for preserving ideal growth conditions and turning biomass into biofuels (Slade & Bauen, 2013). Even with technological developments, achieving market competitiveness is complex since the cost of manufacturing algal biofuels presently ranges from \$2.5 to \$7.5 per gallon. The development of more effective photobioreactors and the integration of renewable energy sources, which can significantly lower running costs, strongly relate the economic viability of algal biofuels to developments in farming technologies.

There are several ways to reduce these costs and increase the economy of algae biofuel production. Economies of scale through increased production facilities, and higher demand for algal biofuels, would make unit cost reduction possible. The researchers can offset expenses by integrating algae farming with current industrial operations, such as wastewater treatment and CO_2 capture from industrial emissions, exploring alternative revenue streams, or reducing current costs (Roberts et al., 2013). As technology improved to use less energy and be more efficient, costs decreased. This made it possible to extract lipids using magnetic nanoparticles for harvesting (Mendes et al., 2003; Vandamme et al., 2012) and pretreatment with supercritical CO_2.

Overall, lowering production costs and increasing co-product value will be key to reaching economic feasibility for algae biofuels. Other revenue streams from co-products, such as animal feed, bio-based chemicals, and fertilizers derived from residual biomass, decrease the overall production cost, thereby boosting the overall profitability of algal biofuel generation. Such potential co-products have the potential to enhance the economy by contributing an additional \$100 to \$150 per tonne of algal biomass (Leow et al., 2018). Applying the biorefinery model, which produces many different products from a single source without Waste, is another way to improve economic sustainability for algal biofuels (Milledge, 2010).

The production of algae biofuels is associated with significant economic challenges, mainly due to the high cultivation, harvesting, and conversion costs as shown in **Table 7**. Despite the high productivity potential of algae, current methods remain expensive, limiting their competitiveness with fossil fuels and other biofuel sources (Morales et al., 2019)

3.4.2 Market potential and financial incentives

Particularly in sectors like aviation, marine shipping, and heavy-duty transportation, where renewable energy is becoming increasingly important, the commercial potential for algal biofuels is noteworthy. Because they may be created without conflicting with food crops for land and water and they fit with current fuel infrastructure, algae biofuels notably appeal (Chisti, 2007). Growing demand for sustainable and renewable energy sources will help the worldwide biofuel business to expand.

The expansion of the algae biofuel industry depends much on governments. Subsidies, tax credits, and grants for research and development,, among other financial incentives,, help reduce obstacles and inspire investment. Specifically, in the United States requiring the mixing of renewable fuels with petroleum-based fuels, renewable fuel standard (RFS) guarantees a market for producers of biofuels (Reidmiller et al., 2018; Wang et al., 2018; Yang et al., 2022). Likewise, the European Union's Renewable Energy Directive (RED) specifies goals for the use of renewable energy in transportation, therefore providing chances for algae biofuels to acquire market share (Kacperska et al., 2021; Villarreal et al., 2020).

3.4.3 Policy recommendations for algae biofuel development

Governments must enact particular and practical policies to guarantee the effective acceptance and commercialization of algal biofuels shown in **Table 8**.

Table 8. Successful policy implementations as models for algae biofuels

No	Policy Model	Description	Potential Application for Algae Biofuels
1	U.S. renewable fuel standard	Mandates blending of renewable fuels with petroleum	Mandate algae biofuel blending in transportation
2	European RED	Sets targets for renewable energy use in transportation	Set targets for algae biofuels in the EU market
3	Brazil's Proálcool program	Incentivized ethanol production and use	Provide financial incentives for algae biofuels

[1](Reidmiller et al., 2018); [2](Kacperska et al., 2021; Villarreal et al., 2020); and [3](Pore et al., 2022; Sharma et al., 2023)

doi: 10.14710/teknik.v46i1.67532

First, governments should give focused funding for research and development (R&D) projects aiming at overcoming the technical obstacles of algae biofuel production, such as improving strain selection, enhancing lipid extraction methods, and developing more efficient farming systems (Gerbens-Leenes et al., 2014; Pore et al., 2022; Villarreal et al., 2020). Second, policy frameworks should support market adoption using measures including mandated higher blending ratios of algae biofuels with conventional fuels, tax incentives for consumers who choose biofuel alternatives, and carbon pricing mechanisms that render fossil fuels less economically appealing (Reidmiller et al., 2018; Wang et al., 2018; Yang et al., 2022). Third, effective policies developed in other biofuel industries could be modified for algae biofuels. Brazil's Proálcool program, which encouraged the manufacture and consumption of ethanol, might provide a model for creating incentives for algal biofuels (Pore et al., 2022; Sharma et al., 2023). Widespread acceptance of algae biofuels depends on its inclusion in current energy policies, including targets for emissions reductions and renewable energy sources. Fourth, international collaboration and technology transfer should be promoted to ensure that developing countries can participate in and benefit from the algae biofuel industry. To boost the worldwide biofuel trade, this covers technical support, easing access to global markets, and harmonizing policies across borders (German et al., 2011)

3.4.4 Global perspective and future directions

It is impossible to overestimate worldwide cooperation's role in developing the algae biofuel sector. In particular, developing nations stand to gain much from the acceptance of algae biofuels since they might offer a sustainable energy source and stimulate economic growth. Overcoming the obstacles confronting algae biofuels and attaining general adoption will depend on international alliances in research, technology transfer, and policy creation (Zinoviev et al., 2010).

The ongoing innovation in farming, harvesting, and processing techniques will determine how successful algal biofuels will be. Further improving the sustainability of algal biofuels could be the creation of hybrid systems combining solar or wind energy sources with algae growing under them. Furthermore, investigating the function of algal biofuels in wastewater treatment and carbon capture and use (CCU) offers fresh chances to improve their financial and environmental feasibility.

3.5 Challenges and Future Directions

3.5.1 Technical challenges

Scaling up algal biofuel output presents technical difficulties with several dimensions. First, a primary concern is the scalability of algae growing. Although laboratory-scale production shows promise, moving to commercial-scale operations requires overcoming several challenges, including the high costs connected with photobioreactors and open pond systems, contamination risks, and the need for significant water and nutrient inputs (Slade & Bauen, 2013). Another great difficulty is the efficiency with which algae can be gathered and processed. Energy-intensive current harvesting techniques such as flocculation and centrifugation help to explain the high general cost of production by their energy consumption (Gultom & Hu, 2013). Though they present possible solutions, advances in harvesting technologies such as magnetic nanoparticles need more study and development for mass deployment (Vandamme et al., 2012).

3.5.2 Environmental considerations

Algae biofuels present a more environmentally sustainable alternative to fossil fuels but are not without environmental challenges as shown in **Table 9**, (Clarens et al., 2010)). Water and resource use is a significant concern, particularly in regions where water scarcity is already a pressing issue. While algae can be grown in effluent or saline water, integrating these methods into mass production systems creates logistical and technical difficulties. Moreover, if not controlled sustainably, the great nutrient demand of algae—especially for nitrogen and phosphorus—may pressure local resources. Strategies to assist in reducing these environmental effects are efficient fertilizer recycling inside the farming system and using wastewater as a nutrient supply (Clarens et al., 2010).

Large-scale algae farming, especially in open systems, runs dangers for nearby ecosystems and species. Non-native or genetically altered algae species could have unexpected ecological effects, including the displacement of native species or the start of damaging

Table 9. Environmental considerations in algae biofuel production

No	Environmental Aspect	Challenges	Potential Solutions
1	Water use	High demand, potential strain on resources	Use of saline water, wastewater, and recycling
2	Nutrient requirements	High nutrient demand, local resource strain	Nutrient recycling, integrated wastewater use
3	Biodiversity impact	Risk of invasive species, algal blooms	Closed systems, strict management practices

doi: 10.14710/teknik.v46i1.67532

algal blooms (Stephenson et al., 2010). Although strict management techniques and closed farming systems help to reduce these hazards, the possibility of environmental effects still causes excellent worry.

3.5.3 Economic and policy challenges

The economic viability of algae biofuels is another significant challenge. Driven by the phases of farming, harvesting, and processing, the high production costs of the fuels impede their competitiveness with other fuels (Morales et al., 2019). Although genetic and metabolic engineering solutions are under investigation to increase biomass and lipid output, these approaches demand significant time and money to develop (Morales et al., 2019). Moreover, the acceptance of genetically modified (GE) algae among regulatory authorities and industry players presents more challenges that need to be negotiated to enable general use (Villarreal et al., 2020).

Market competitiveness is a critical issue, especially given the fluctuating prices of fossil fuels and the current high cost of algae biofuels. Reducing expenses mostly depends on developing affordable manufacturing techniques and attaining economies of scale. Establishing a market for algal biofuels will also call for supporting laws like mandates for renewable fuel consumption, tax incentives, and subsidies (Slade & Bauen, 2013).

Policy and regulatory frameworks must also be developed to support the growth of the algae biofuel industry. The complexity and variability of regulatory frameworks across different regions can create barriers to international trade and market expansion. Harmonizing standards and certification processes and ensuring long-term policy stability will be crucial for fostering the development of algae biofuels (Kacperska et al., 2021; Villarreal et al., 2020).

3.5.4 Future directions

The future of algae biofuels lies in addressing the technical, environmental, and economic challenges discussed in this chapter. Key areas for future research including, integration of algae biofuels into existing energy systems; developing hybrid farming systems combining algae generation with other renewable energy sources, such as solar or wind, could improve the sustainability and efficiency of algal biofuel manufacture. Furthermore, incorporating algae biofuels into current energy systems, including oil refineries, offers possibilities and difficulties that demand more research (Andersson et al., 2020). Development of advanced genetic and bioprocessing technologies. Improving the lipid content and growth rates of algal strains depends on ongoing developments in genetic engineering and bioprocessing technology, which makes them more fit for mass biofuel generation (Driver et al., 2014). Furthermore, addressing the issues related toto genetically modified algae will depend on research on stronger genetic tools and public participation tactics (He et al., 2014). Exploration of algae's role in carbon capture and utilization (CCU). An interesting path for the following studies is the possibility of algal biofuels helping to absorb and use carbon emissions. Combining algae farming with carbon capture technologies could help to drastically lower greenhouse gas emissions while generating sustainable biofuels (Khandelwal et al., 2023).

Research on the environmental impacts of water and nutrient use, biodiversity issues, and lifetime emissions or energy payback is crucial for the sustainability of algal biofuel production. Sustainable practices such as land, water, and nutrient recycling (Stephenson et al., 2010), the use of non-arable lands for cultivation, and the use of saline waters without causing problematic effects on those environments are necessary to realize the full environmental benefits associated with algal biofuels.

As the biofuels industry evolves, worldwide collaboration will become more important than ever. Global cooperation in research, technology transfer, and policy development is likely crucial for the production of algal biofuels to mature and become market-acceptable. In a multi-national collaboration, this could enhance the versatility and profitability of biofuels in developing nations, enabling researchers to leverage global resources and knowledge on chemical engineering processes while also fostering the development of local biorefining industries that contribute to global energy sustainability (Zinoviev et al., 2010).

4. Conclusion

Algae biofuel is a viable technology that can replace fossil oil in the transportation sector. It represents an opportunity for reducing carbon dioxide emissions from transporting people, goods, or services globally. Due to their high lipid content and adaptability to diverse environments, algae are the primary biological choice for biofuel production. Algal biofuel production has come a long way quickly thanks to new technologies like photobioreactors for high-density cultivation systems and genetic engineering to increase lipid yield, which makes it easier to scale up. In addition, energy-efficient production methods such as magnetic nanoparticle-assisted extraction provide potential means of minimizing the harvesting costs (thereby increasing sustainability). However, algae biofuels must tackle economic and policy obstacles to achieve commercialization. Well-defined policy recommendations (for example, achieving global standards for biofuels produced by algae and providing economic support) are necessary to help the industry prosper. Moreover, phases of international collaboration and technology transfer will help pave the way to commercialization, particularly in developing countries that can capitalize on global expertise and resources. This paper proposes that future research adopt an integrated

doi: 10.14710/teknik.v46i1.67532

biorefinery approach to maximize the yield of products from algal biomass. This will create a complete and efficient value chain that makes the business more profitable. The researchers examine these technologies, including those for carbon capture and utilization (CCU) and wastewater treatment, in light of the factors driving new technological advancements, to boost the sustainability and profitability of algae biofuels. uels. To realize the full potential of algae biofuels, the researchers need further research and development within a supportive policy framework at an international level. Meeting these challenges and opportunities, biofuels from algae have the potential to make a significant impact on sustainable transportation (and thus adaptation) within an era that requires both.

Acknowledgements

This article is published in Journal Teknik as part of an agreement with Traction Energy Asia to showcase winners of "Strategi Transisi Energi Berkeadilan di Sektor Transportasi" conference's call for papers. While published under this special arrangement, the paper has undergone Journal Teknik's comprehensive peer review process to ensure scholarly quality and merit.

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doi: 10.14710/teknik.v46i1.67532