Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 05 July 2026
Revised 13 Aug 2026
Accepted 30 Aug 2026

Natural Resources for Human Health 2026, Vol. 6 (20s): 1230–1239

KEYWORDS:
Biodiesel, microalgae, algae oil extraction, alkaline transesterification, biofuel production.

Biodiesel Production from Naturally Occurring Green Algae of the Al-Zawiya Coast, Libya

Awatif Meelad[1], Nadya Hussin AL Sbani[2], Omar Sultan[3], Alaa Kareem Mohammed[4], Luttfia M. Hadod[5], Eman Hussin Abobaker[6], Haneen Alhanish[7], Gumma A. Abodera[8], Alayadi Almabrouk Gwaider[9]

[1,2,3,6]Department of Chemical Engineering, Faculty of Oil, Gas, Renewable Energy Engineering, University of Zawia, Libya
[4]Department of Chemical Engineering, Higher Institute of Science and Technology, Al-Khums, Libya
[5]Department of Biochemistry, College of Health and Medical Technology, AlShaab University, Baghdad, Ira

ABSTRACT: Depleting fossil fuel resources, growing environmental concerns, and the global pursuit of sustainable development have driven the development of renewable energy alternatives, such as biodiesel from algae biomass. This study investigates biodiesel production from naturally occurring green algae collected from the Al-Zawiya coast, Libya, and evaluates its fuel properties according to ASTM standards. The algae were dried, ground, and Soxhlet-extracted with n-hexane to produce algae oil. The algae biomass yielded 7.96% oil. The oil was converted to biodiesel via alkaline transesterification using potassium hydroxide (KOH) as the catalyst. The process was carried out at 63°C with a methanol-to-oil molar ratio of 3:1, resulting in a biodiesel yield of approximately 90% (before washing). The produced biodiesel exhibited a kinematic viscosity of 5.24 mm^2/s, a density of 888 kg/m^3, a flash point of 110°C, a cloud point of -12.4°C, a pour point of -5.7°C, and an estimated cetane number of 49. The values for viscosity, flash point, and cetane number fell within the limits specified by the American Society for Testing and Materials (ASTM D6751) standard; however, this standard does not include specific requirements for density or low-temperature flow properties. The results indicate that green algal biomass is a promising feedstock for biodiesel production, although its oil content was found to be low. Furthermore, additional research covering engine performance, emissions, storage stability, production costs, and life cycle assessment is required before the potential for commercial application can be considered

1. INTRODUCTION

The rapid increase in global energy demand, together with the environmental impacts associated with fossil fuel consumption, and the imperative goals of sustainable development have intensified the search for sustainable and renewable energy resources. Conventional fossil fuels remain the primary source of global energy; however, their excessive use contributes significantly to greenhouse gas emissions, as carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter emissions contribute to climate change, air pollution, and depletion of non-renewable resources (Foqha et al., 2026). Among renewable energy alternatives, biodiesel has received considerable attention because it is biodegradable, non-toxic, renewable, and capable of reducing harmful exhaust emissions compared with conventional diesel fuel (Oyetola Ogunkunle et al., 2021). Biofuels are classified according to the raw materials used in production. They are derived primarily from edible crops such as

corn, soybeans, sunflowers, and sugarcane. Despite their commercial success, these feedstocks compete directly with food production and require large amounts of agricultural land and freshwater resources (Mishra and Goswami, 2018). Therefore, agricultural waste and cellulosic biomass were used, such as cow and poultry waste. (Sbani and Mohammed, 2023). As well as some non-food oils such as jojoba and castor oil (Sbani et al., 2025). Algae are also considered an important source. Algae are also an important source for biofuels because of their high productivity and environmental sustainability (Fathima Zahra Nashath et al., 2025).

Algae have emerged as one of the most promising feedstocks for biodiesel production due to their rapid growth rate, high photosynthetic efficiency, and substantial lipid accumulation capacity (Chhandama et al., 2023). Unlike terrestrial energy crops, algae can grow on non-arable land using saline water, wastewater, or coastal water without competing with food crops(Aransiola et al., 2023). Furthermore, algae can effectively utilize atmospheric carbon dioxide during photosynthesis, contributing to carbon sequestration and reduction of greenhouse gas emissions. The production of biodiesel from algae generally involves several important stages, including cultivation, harvesting, drying, lipid extraction, transesterification, purification, and fuel characterization. Soxhlet extraction using solvents such as n-hexane remains one of the most commonly used methods for algae oil extraction due to its simplicity and efficiency (Pandey et al., 2024). Alkaline transesterification is widely preferred because of its high conversion efficiency, shorter reaction time, and relatively low operational cost (Velasquez-Orta et al., 2012). The quality and performance of biodiesel are evaluated according to international standards such as ASTM D6751 and EN 14214 (Chen et al., 2015). In this study, naturally occurring green algae collected from the Al-Zawiya coast, Libya, were used as feedstock for biodiesel production. Algae oil was extracted using the Soxhlet extraction technique and converted into biodiesel through alkaline transesterification using potassium hydroxide as a catalyst. The produced biodiesel was subsequently characterized according to ASTM standards to evaluate its suitability as an alternative renewable fuel.

2. MATERIALS AND METHODS

The production of biodiesel from algae biomass involved several sequential stages, including algae collection and preparation, oil extraction, oil pre-treatment, transesterification, biodiesel purification, and fuel characterization. All experiments and physicochemical measurements were conducted in triplicate, and the reported values represent the average of the obtained results. The overall experimental procedure was conducted in the laboratories of the Faculty of Education, Al-Zawiya, Libya. A schematic representation of the biodiesel production process is illustrated in Figure 1.

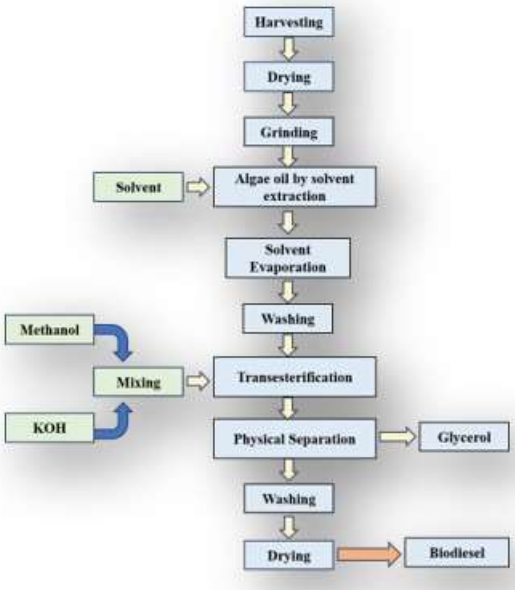


Figure 1. Flowchart of biodiesel production from algae biomass through alkaline transesterification.

2.1 Collection and Preparation of Algae Biomass

Samples of green algal biomass were collected manually in September 2025 from the Mediterranean coastal area near the Zawiya refinery in northwestern Libya (approximate coordinates: 32.77° N, 12.72° E). The algae were identified only visually as green algae, and no taxonomic identification was performed. The study focused on evaluating locally available green algae for potential use in biodiesel production, rather than examining a single isolated species. A total of 4,396 g of fresh biomass was collected and subsequently washed thoroughly with water to remove sand, salts, and other impurities. The washed biomass was then sun-dried for two days at temperatures ranging from 27°C to 35°C to reduce its moisture content, yielding 1,730 g of dried algae. In a subsequent step, the biomass was mechanically ground into a powder (weighing 1,721 g) to increase its surface area and improve the efficiency of oil extraction. Figure 2 illustrates the stages of biomass collection, drying, and grinding.



Figure 2. Preparation stages of algae biomass: (a) collected algae, (b) drying process, and (c) grinding of dried algae.

2.2 Extraction of Algae Oil

Algae oil was extracted using the Soxhlet solvent extraction method due to its high extraction efficiency and simplicity. Approximately 50 g of dried algae biomass was placed inside a cellulose extraction thimble and inserted into the Soxhlet extractor. The extraction solvent was 150 mL of n-hexane. The extraction process was carried out at the boiling temperature of n-hexane (69°C) for 5 h. During extraction, the solvent vaporized, condensed in the condenser, and repeatedly washed the algae biomass, allowing the oil to dissolve into the solvent. The extraction was repeated until a total of 1,721 g of dried algae powder had been processed, giving 137 g of crude algae oil (166 mL).

Following extraction, the solvent-oil mixture was transferred to a rotary vacuum evaporator to recover the solvent and obtain crude algae oil. The solvent was evaporated at 69°C for approximately 35 min, leaving the extracted oil in the evaporation flask. The Soxhlet extraction apparatus used in this study is shown in Figure 3.

The percentage oil yield was calculated according to Equation (1):

$$\%\text{Algae oil yield} = (\text{Weight of extracted oil} \times 100\%) / (\text{Weight of dried algae Sample}) \quad (1)$$



Figure 3. Soxhlet extraction apparatus used for algae oil extraction.

2.3 Pre-treatment and Degumming of Algae Oil

The extracted algae oil was subjected to acid degumming to remove phospholipids, gums, and impurities that could negatively affect the transesterification process. Initially, 166 mL of algae oil was heated to 80°C under continuous stirring using a magnetic

stirrer. Subsequently, 3 mL of 80% sulfuric acid solution was gradually added to the heated oil. The mixture was stirred thoroughly and washed with 50 mL of distilled water before being transferred to a separating funnel and allowed to settle for 30 min. The separated gum layer was removed, and the remaining oil was centrifuged to eliminate residual impurities and moisture. Finally, the treated oil was dried before biodiesel production.

2.4 Biodiesel Production by Alkaline Transesterification

Biodiesel production was carried out using the alkaline transesterification method. The reaction system consisted of a 500 mL double-neck flat-bottom flask equipped with a reflux condenser, thermometer, and magnetic stirrer with heating capability, as illustrated in Figure 4. Initially, 166 mL of algae oil (approximately 137 g) was heated to 63°C. A methoxide solution was prepared by dissolving potassium hydroxide(KOH, approximately 1.37 g, i.e., 1 wt.% relative to the oil mass) in methanol at a methanol-to-oil molar ratio of 3:1. The methoxide solution was gradually added to the preheated algae oil while continuously stirring the mixture for 25 min. After completion of the reaction, the mixture was transferred to a separating funnel and allowed to settle at room temperature for 24 h. Two distinct layers formed: biodiesel (upper layer) and glycerol (lower layer). The glycerol layer was carefully removed, and the biodiesel was collected for purification.



Figure 4. Experimental setup for alkaline transesterification and phase separation of biodiesel and glycerol.

The crude biodiesel was purified to remove residual catalyst, methanol, soap, and glycerol impurities. Washing was performed using warm distilled water containing 1–2 drops of sulfuric acid for neutralization of residual alkaline catalyst. Several washing cycles with distilled water were carried out until a clear wash water phase was obtained. The purified biodiesel was subsequently heated at 110°C for 2 h to remove residual moisture and excess methanol. The biodiesel yield was calculated using Equation (2):

$$\text{Biodiesel yield (\%)} = \frac{\text{Volume of biodiesel obtained (mL)}}{\text{Volume of oil used (mL)}} \times 100\% \quad (2)$$

2.5 Characterization of Biodiesel

2.5.1 Kinematic Viscosity (μ)

The kinematic viscosity was determined at 40°C according to ASTM D445 using a calibrated glass capillary viscometer in a Setavis (UK) kinematic viscosity bath. Approximately 10 mL of biodiesel was introduced into the viscometer and equilibrated in the bath at 40°C for 30 min before measurement. The efflux time and the kinematic viscosity were recorded. The viscosity was calculated using Equation (3):

$$\mu = C \times t \quad (3)$$

where μ is the kinematic viscosity (mm^2/s), C is the calibration constant of the viscometer, and t is the flow time (s).

2.5.2 Density

Density was determined gravimetrically at room temperature using a clean, dry 50 mL volumetric cylinder. The empty cylinder was weighed (W_0), filled with biodiesel to the 50 mL mark, and reweighed (W_1). This gravimetric method is not one of the ASTM density methods (D1298 or D4052), and the value is therefore reported as an approximate value. Density was calculated according to Equation (4):

$$\text{Density} = \text{Mass} / \text{Volume} \quad (4)$$

2.5.3 Flash Point and Fire Point

The flash point was determined using a Pensky-Martens closed-cup tester according to ASTM D93, in which the sample is heated at a controlled rate, and an ignition source is passed over the surface at intervals, the lowest temperature at which the vapors ignite being recorded. The fire point was determined using the same apparatus by continuing heating until the vapors burned for at least 5 s after ignition.

2.5.4 Cloud Point and Pour Point

The cloud point was determined according to ASTM D2500 by cooling the sample at a specified rate and recording the temperature at which a cloud was first observed at the bottom of the test jar. The pour point was determined according to ASTM D97 by cooling the sample at a specified rate and examining it for flow at 3°C intervals, the lowest temperature at which movement was observed being recorded.

2.5.5 Aniline Point

The aniline point was determined according to ASTM D611 by mixing 10 mL of biodiesel with 10 mL of aniline, heating the mixture with stirring at a controlled rate until the two phases became miscible, and then cooling it at a controlled rate and recording the temperature at which the phases separated.

2.5.6 Cetane Number

The cetane number was not measured by the engine test of ASTM D613; it was estimated from the aniline point and API gravity using the correlation of Boerlage and Broeze (Equation 5). The reported value is therefore an estimated cetane index and not a measured cetane number.

$$\text{Cetane Index} = \frac{\text{Aniline point (°C)} \times \text{API Gravity}}{10} \quad (5)$$

2.5.7 Quality Control and Compliance Assessment.

All measurements were performed in triplicate, and the average values are reported. Measured properties were compared with the limits of ASTM D6751 for viscosity (1.9–6.0 mm^2/s), flash point (93°C min), and cetane number (47 min). Density and cold-flow properties (cloud and pour points) are not specified in ASTM D6751 and were compared with ranges reported in the literature for reference only.

3. RESULTS AND DISCUSSIONS

3.1 Algae Oil Extraction

The extraction of lipids from algae biomass represents one of the most important stages in biodiesel production because the quantity and quality of the extracted oil directly influence biodiesel yield and fuel properties. In the present study, Soxhlet extraction using n-hexane as a solvent successfully extracted algae oil from naturally collected green algae biomass. The extraction process yielded approximately 3.98 g of oil from 50 g of dried algae biomass, corresponding to an oil yield of 7.96%.

The obtained oil yield is relatively low compared with values reported for optimized microalgae cultivation systems, where lipid contents may range from 20–50% under controlled environmental conditions (Pandey et al., 2024). However, the obtained yield is considered acceptable for naturally occurring coastal algae collected without nutrient optimization or controlled cultivation. The relatively low lipid content may be attributed to several factors, including algae species variation and environmental conditions, sunlight exposure, nutrient availability, salinity, and harvesting season. Similar observations were reported by others, who noted that lipid productivity in macroalgae and naturally harvested algae is generally lower than that of laboratory-cultivated microalgae (McKinley and Ozbay, 2026).

Solvent type, extraction temperature, extraction duration, and algae biomass particle size can also influence Soxhlet extraction efficiency. In this study, grinding increased the biomass surface area and improved solvent penetration, thereby enhancing lipid recovery. In addition, n-hexane was selected because of its high affinity for non-polar lipids and its widespread use in biodiesel research (Baig et al., 2018).

3.2 Biodiesel Production by Transesterification

The extracted algae oil was converted into biodiesel through alkaline transesterification using potassium hydroxide (KOH) as a homogeneous catalyst. The transesterification process produced two distinct layers after 24 h of settling: biodiesel in the upper layer and glycerol in the lower layer, confirming successful conversion of triglycerides into fatty acid methyl esters (FAME). The separation of glycerol from biodiesel is shown in Figure 6.



Figure 6. Separation of biodiesel and glycerol after transesterification.

The biodiesel yield, calculated on a volume basis, was approximately 90% before washing (149 mL of crude biodiesel from 166 mL of oil, i.e., 89.8%). After washing and drying, 134 mL was recovered, corresponding to about 81% of the initial oil volume, and the difference is attributed to losses during washing, indicating high reaction effectiveness. The yield obtained before washing indicates high reaction effectiveness under the selected operating conditions. The relatively high yield is attributed to alkaline catalysis, which offers fast reaction kinetics and high conversion efficiency for oils with low free fatty acid content. The reaction temperature of 63°C was selected near the boiling point of methanol to improve the reaction rate while minimizing excessive methanol evaporation. The high yield achieved indicates effective reaction, comparable to recent findings in optimized biodiesel synthesis and green catalytic pathways (Rashid et al., 2023).

The methanol-to-oil molar ratio and catalyst concentration significantly influence biodiesel production efficiency. In the present study, a 3:1 methanol-to-oil molar ratio and 1 wt.% KOH catalyst concentration was used successfully to obtain a high biodiesel yield. Previous studies report that increasing methanol concentration can enhance ester conversion; however, excessive methanol may complicate glycerol separation and increase purification requirements (Rashid and Anwar, 2008). At larger scale, methanol consumption and recovery, together with the extensive water washing required to remove the homogeneous KOH catalyst from the product (Mustafa et al., 2024), would directly affect process cost and environmental burden and should be evaluated in a techno-economic assessment. Furthermore, optimizing reaction variables and thermal conditions is crucial for maximizing FAME yields, consistent with advanced green catalytic systems using waste-derived frameworks(Mohammed et al., 2023). Some biodiesel losses were observed during purification and washing processes due to emulsification and removal of impurities. Nevertheless, the obtained biodiesel yield remained relatively high compared with several previous algae biodiesel studies. The final purified biodiesel is shown in Figure 7.



Figure 7. Purified biodiesel.

3.3 Physicochemical Properties of the Produced Biodiesel

The physicochemical properties of the produced algae biodiesel were evaluated using the methods described in Section 2.5 and compared with ASTM D6751. The measured properties are presented in Table 1.

Table1. Physicochemical properties of the produced algae biodiesel.

Property	Unit	Test Method	ASTM D6751 limit	Produced Biodiesel
Kinematic viscosity at 40°C	mm^2/s	ASTM D445	1.9–6.0	5.24
Density	kg/m^3	Gravimetric[a]	Not specified	888
Flash point	°C	ASTM D93	>93	110
Fire point	°C	Pensky-Martens	Not specified	122
Pour point	°C	ASTM D97	Not specified	−5.7
Cloud point	°C	ASTM D2500	Report	−12.4
Aniline point	°C	ASTM D611	Not specified	26
Cetane number	---	Estimated[b]	>47	49

[a] Not an ASTM density method (D1298 or D4052). [b] Calculated from aniline point and API gravity; not measured by ASTM D613

Viscosity, flash point, and estimated cetane number met the ASTM D6751 limits, whereas density and cold-flow properties are not specified in that standard and are reported for reference.

3.4 Comparison of Biodiesel Properties with ASTM Standards and Previous Studies

To evaluate the quality of the produced biodiesel, the measured fuel properties were compared with ASTM D6751 standards and previously published algae biodiesel studies, as presented in Table 2. The comparison shows that the properties are comparable to previously reported algae biodiesel values, with viscosity, flash point, and estimated cetane number meeting the ASTM D6751 limits.

The kinematic viscosity of the produced biodiesel was 5.24 mm^2/s, which falls within the ASTM acceptable range. Viscosity is one of the most important fuel properties because it influences atomization, fuel injection, and combustion performance in diesel engines. Excessively high viscosity can result in poor atomization and incomplete combustion, while low viscosity may reduce lubrication efficiency. The obtained value is comparable to those reported for algae biodiesel (Mariyam et al., 2026). This indicates that the produced biodiesel has suitable flow characteristics.

Table 2. Comparison of algae biodiesel properties with ASTM standards and literature data

Property	This Study	ASTM D6751	Previous Studies	Reference
Viscosity (mm^2/s)	5.24	1.9–6.0	4.8–5.7	(Nautiyal et al., 2014)
Density (kg/m^3)	888	Not specified (EN 14214:860-900)	870–890	(Johnson and Wen, 2009)
Flash Point (°C)	110	>93	100–120	(Chintala et al., 2017)
Cloud Point (°C)	−12.4	Report	−10 to −13	(Hossain et al., 2008)
Cetane Number	49	>47	48–52	(Pandey et al., 2024)

The density of the produced biodiesel was 888 kg/m^3, which lies within the 860–900 kg/m^3 range specified in EN 14214; ASTM D6751 does not specify a density limit. Biodiesel density depends mainly on fatty acid composition and purity. Appropriate density contributes to improved combustion efficiency and energy output. Similar density values have been reported in several algae biodiesel studies (Johnson and Wen, 2009). The flash point of the produced biodiesel was 110°C, which exceeds the ASTM minimum requirement of 93°C. A higher flash point improves fuel safety during transportation and

storage because it reduces flammability risks. The measured fire point of 122°C is consistent with the high flash point and indicates safe handling characteristics.

Cold flow properties, including cloud point and pour point, are important indicators of biodiesel behavior under low-temperature conditions. The cloud point of −12.4°C and pour point of −5.7°C are reported for reference, since ASTM D6751 requires only that the cloud point be reported. These values suggest that the biodiesel may remain fluid under moderate cold conditions, although cold-flow behavior depends strongly on fatty acid composition, which was not determined here. The estimated cetane number of the produced biodiesel was 49, which exceeds the ASTM D6751 minimum of 47. Cetane number is an important indicator of ignition quality and combustion performance in diesel engines. Higher cetane values reduce ignition delay and improve combustion efficiency while minimizing engine knocking and exhaust emissions. The extraction of biofuel from algae faces challenges stemming from seasonal and spatial variations in biomass composition and lipid content, driven by environmental fluctuations such as light and temperature (Chisti, 2007). In the present study, the algae were collected from a single location in September 2025, so the oil yield of 7.96% cannot be assumed to be representative, and sampling across seasons and sites would be needed; where a stable supply is required, controlled cultivation may be considered. To achieve commercial viability, the technical, economic, and environmental feasibility must be assessed through life-cycle analysis (Uihlein et al., 2023). Regarding chemical processes, optimizing the methanol-to-oil ratio and catalyst concentration is crucial for cost reduction (Palayan et al., 2025); the 3:1 ratio and 1 wt.% KOH used here were not optimized. Production cost was not evaluated in this study; given the low oil content (about 12.6 kg of dried biomass per kg of oil), the costs of collection, drying, and solvent extraction are likely to be significant. Furthermore, the sustainable repurposing of by-products such as glycerol and the residues remaining after oil extraction is essential to support a circular economy (Ahmad, I., Khan, M., 2023). Finally, transitioning to practical application requires comprehensive testing on dynamometer-coupled engines, monitoring fuel stability during long-term storage, and analyzing emissions to ensure real-world performance (Zhang et al., 2022)

Overall, the results indicate that biodiesel produced from naturally occurring green algae has fuel properties comparable to values reported for other biodiesels, with viscosity, flash point, and estimated cetane number meeting the ASTM D6751 limits. These findings suggest the potential of green algae biomass as a feedstock for biodiesel production, subject to the further testing required for commercial application.

4. CONCLUSION

This study produced biodiesel from naturally occurring green algae collected along the Al-Zawiya coast, Libya, using Soxhlet extraction and alkaline transesterification. The algae biomass yielded 7.96% oil, and the transesterification step gave a biodiesel yield of approximately 90% before washing under the conditions applied. The kinematic viscosity, flash point, and estimated cetane number of the produced biodiesel met the ASTM D6751 limits, while density and cold-flow properties, which are not specified in that standard, were within ranges reported for biodiesel in the literature. These laboratory-scale results indicate that locally available green algae can serve as a potential feedstock for biodiesel production. However, the low oil yield, the variability of naturally harvested algal biomass, the use of a non-optimized 3:1 methanol-to-oil ratio with a non-recoverable homogeneous catalyst, and the management of by-products and production cost remain challenges. In addition, engine performance and emission tests, storage stability evaluation, and a life-cycle assessment are needed before commercial-scale application can be established. Future work should therefore include multi-season and multi-site sampling, species identification and fatty acid profiling, optimization of the reaction conditions, and techno-economic and life cycle analyses.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the technical and logistical support provided by the Faculty of Oil, Gas, Renewable Energy Engineering, University of Zawia, Libya, and the Al-Khwarizmi College of Engineering, University of Baghdad, Iraq, for facilitating the experimental work and analysis.

AUTHOR CONTRIBUTIONS

Awatif Meelad: Supervision, Conceptualization, Writing.

Nadya Hussin AL Sbani: Methodology, Writing.

Omar Sultan: Investigation.

Omar Hamed Jehawi: Review & Editing

Alaa Kareem Mohammed: Review & Editing

Alayadi Almabrouk Gwaider: Resources, Data Curation, Laboratory Analysis.

CONFLICT OF INTEREST

The authors declare no competing financial or personal interests that could have influenced the work.

ETHICS STATEMENT

Ethical approval and informed consent were not required for this study because it involved collecting naturally occurring green algae from coastal areas, not human participants or live animals.

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request.

REFERENCES

[1] Ahmad, I., Khan, M., 2023. Life cycle assessment of microalgae-derived biodiesel. The International Journal of Life Cycle Assessment 28, 590–609. https://doi.org/10.1007/s11367-023-02150-z

[2] Aransiola, S.A., Victor-Ekwebelem, M.O., Leh-Togi Zobeashia, S.S., Maddela, N.R., 2023. Sources and techniques for biofuel generation, in: Shah, M.P. (Ed.), Green Approach to Alternative Fuel for a Sustainable Future. Elsevier, pp. 311–323. https://doi.org/10.1016/B978-0-12-824318-3.00026-6

[3] Baig, R.U., Malik, A., Ali, K., Arif, S., Hussain, S., Mehmood, M., Sami, K., Mengal, A.N., Khan, M.N., 2018. Extraction of oil from algae for biodiesel production, from Quetta, Pakistan. IOP Conf. Ser.: Mater. Sci. Eng. 414, 012022. https://doi.org/10.1088/1757-899X/414/1/012022

[4] Chen, H., Zhou, D., Luo, G., Zhang, S., Chen, J., 2015. Macroalgae for biofuels production: Progress and perspectives. Renewable and Sustainable Energy Reviews 47, 427–437. https://doi.org/10.1016/j.rser.2015.03.086

[5] Chhandama, M.V.L., Ruatpuia, J.V.L., Ao, S., Chetia, A.C., Satyan, K.B., Rokhum, S.L., 2023. Microalgae as a sustainable feedstock for biodiesel and other production industries: Prospects and challenges. Energy Nexus 12, 100255. https://doi.org/10.1016/j.nexus.2023.100255

[6] Chintala, V., Kumar, Suresh, Pandey, J.K., Sharma, A.K., Kumar, Sagar, 2017. Solar thermal pyrolysis of non-edible seeds to biofuels and their feasibility assessment. Energy Conversion and Management 153, 482–492. https://doi.org/10.1016/j.enconman.2017.10.029

[7] Chisti, Y., 2007. Biodiesel from microalgae. Biotechnology Advances 25(3), 294–306. https://doi.org/10.1016/j.biotechadv.2007.02.001

[8] Foqha, T., Refaat, S.S., Mohammed, A., Farrag, M., Gamal, H., 2026. Renewable energy sources: Progress, challenges, and environmental benefits. Renewable and Sustainable Energy Reviews 240, 117167. https://doi.org/10.1016/j.rser.2026.117167

[9] Hossain, A.B.M.S., Salleh, A., Boyce, A.N., Chowdhury, P., Naqiuddin, M., 2008. Biodiesel fuel production from algae as renewable energy. American Journal of Biochemistry and Biotechnology, 4.

[10] Johnson, M.B., Wen, Z., 2009. Production of Biodiesel Fuel from the Microalga Schizochytrium limacinum by Direct Transesterification of Algal Biomass. Energy Fuels 23, 5179–5183. https://doi.org/10.1021/ef900704h

[11] Mariyam, S., Alherbawi, M., McKay, G., Al-Ansari, T., 2026. Toward sustainable biofuels in arid regions: Bioprospecting Qatar's flora. Industrial Crops and Products 240, 122608. https://doi.org/10.1016/j.indcrop.2025.122608

[12] McKinley, K., Ozbay, G., 2026. The power of microalgae: Cutting-edge applications and groundbreaking innovations. New Biotechnology 93, 325–340. https://doi.org/10.1016/j.nbt.2026.04.003

[13] Mishra, V.K., Goswami, R., 2018. A review of production, properties and advantages of biodiesel. Biofuels 9, 273–289. https://doi.org/10.1080/17597269.2017.1336350

[14] Mohammed, A.K., Alkhafaje, Z.A., Rashid, I.M., 2023. Heterogeneously catalyzed transesterification reaction using waste snail shell for biodiesel production. Heliyon.

[15] Mustafa, H.M.M., Abdelsadak, M.Y., Gouda, Z.A., Mokhtar, M.M., Mostafa, A.M., Ghareb, M.A., Hossam, A.E., Mohamed, O.S., Mohamed, R.M., El-Hadidy, S., 2024. The Effect of Temperature, Time, and Methanol Concentration

on Enhancing the Yield of Biodiesel Production of Castor and Rapeseed Seeds via the Transesterification Process. Egyptian Journal of Chemistry 67 (SI: M. R. Mahran), 371–377. https://doi.org/10.21608/ejchem.2024.257668.9040

[16] Nashath, F.Z., Ng, Y.J., Khoo, K.S., Show, P.L., 2025. Current contributions of microalgae in global biofuel production; cultivation techniques, biofuel varieties and promising industrial ventures. Biomass and Bioenergy 201, 108092. https://doi.org/10.1016/j.biombioe.2025.108092

[17] Nautiyal, P., Subramanian, K.A., Dastidar, M.G., 2014. Production and characterization of biodiesel from algae. Fuel Processing Technology 120, 79–88. https://doi.org/10.1016/j.fuproc.2013.12.003

[18] Ogunkunle, O., Ahmed, N.A., 2021. Energy factors affecting environmental pollution for sustainable development goals: The case of India.

[19] Palayan, S., Kings, A. J., Monisha, L. R., & Saravanan, A. (2025). Comprehensive Review of Biodiesel Production from Nonedible Feedstocks: Environmental Impacts and Sustainable Solutions. Journal of Environmental Nanotechnology, 13(4), 257–271. https://doi.org/10.13074/jent.2024.12.243860

[20] Pandey, S., Narayanan, I., Selvaraj, R., Varada Venkatesan, T., Vinayagam, R., 2024a. Biodiesel production from microalgae: A comprehensive review on influential factors, transesterification processes, and challenges. Fuel 367, 131547. https://doi.org/10.1016/j.fuel.2024.131547

[21] Pandey, S., Narayanan, I., Selvaraj, R., Varada Venkatesan, T., Vinayagam, R., 2024. Biodiesel production from microalgae: A comprehensive review on influential factors, transesterification processes, and challenges. Fuel 367, 131547. https://doi.org/10.1016/j.fuel.2024.131547

[22] Rashid, I.M., Abdulwahab, Y.D., Mohammed, A.K., Isahak, W.N.R.W., Jassamc, and B.A., 2023. Modeling and optimization of biodiesel from high free-fatty-acid chicken fat by non-catalytic esterification and mussel-shell-catalyzed transesterification. Journal of Chemical Technology & Biotechnology.

[23] Rashid, U., Anwar, F., 2008. Production of biodiesel through optimized alkaline-catalyzed transesterification of rapeseed oil. Fuel 87, 265–273. https://doi.org/10.1016/j.fuel.2007.05.003

[24] Sbani, N.H.A., Meelad, A., Mohammed, A.K., Alfarid, K., 2023. Impact of Concentration of Cow MANURE ON Biogas Production. International Science and Technology Journal.

[25] Sbani, N.H.A., Meelad, A., Sultan, O., Mohammed, A., Kwadikha, A., Tweib, S., 2025. Biodiesel Production from Castor Oil. Al-Khwarizmi Engineering Journal 21, 1–11. https://doi.org/10.22153/kej.2025.03.001

[26] Uihlein, A., Scherer, C., Prussi, M., 2023. Global Life Cycle and Techno-Economic Assessment of Algal-Based Biofuels. Environmental Science & Technology 57(31), 11541–11551. https://doi.org/10.1021/acs.est.3c01234

[27] Velasquez-Orta, S.B., Lee, J.G.M., Harvey, A., 2012. Alkaline in situ transesterification of Chlorella vulgaris. Fuel 94, 544–550. https://doi.org/10.1016/j.fuel.2011.11.045

[28] Zhang, Y., Zhong, Y., Lu, S., Zhang, Z., & Tan, D. (2022). A comprehensive review of the properties, performance, combustion, and emissions of the diesel engine fueled with different generations of biodiesel. Processes, 10(6), 1178. https://doi.org/10.3390/pr10061178