



Experimental Analysis of an IoT-Based Algal Biodiesel System Using Wastewater

Nasir Akbar

*Department of Mechanical Engineering, University of Engineering & Technology, Mardan
23200, Pakistan*

Faiq Said

*Department of Mechanical Engineering, University of Engineering & Technology, Mardan
23200, Pakistan*

Syed Ishaq Ali Shah

*Department of Mechanical Engineering, University of Engineering & Technology, Mardan
23200, Pakistan*

Ammar Zeb

*Department of Mechanical Engineering, University of Engineering & Technology, Mardan
23200, Pakistan*

Arslan Nawaz

*Department of Mechanical Engineering, University of Engineering & Technology, Mardan
23200, Pakistan*

Muhammad Ahmad

*Department of Mechanical Engineering, University of Engineering & Technology, Mardan
23200, Pakistan*

Abstract

This study experimentally demonstrates a cost-effective and sustainable system for producing high-quality biodiesel from algae cultivated in wastewater. Algal biomass increased from 20 grams to 42 grams over 12 days under continuous white light, achieving a 110 percent growth rate and a net gain of 22 grams. Biodiesel yield improved with drying time, producing 40 milliliters after one day, 90 milliliters after two days, and 120 milliliters after three days from 40 grams of dried algae. Fuel characterization confirmed high energy content with calorific values of 46.63 megajoules per kilogram from Bomb Calorimeter tests at UET Mardan and 45.16 megajoules per kilogram from ASTM D4809 tests at NCPC Foundation, exceeding conventional diesel ranges of 42.0 to 44.5 megajoules per kilogram. An IoT-based monitoring system recorded a temperature of 26.6 degrees Celsius, CO₂ concentration of 404 parts per million, water level of 84 percent, and pH of 6.4, with automated alerts and historical logging to optimize growth and production. The integrated approach confirms algae-derived biodiesel as a high-energy, clean-burning, and scalable alternative to fossil fuels.

Keywords: *Algae, Biodiesel, IoT, Wastewater, Renewable Energy, Arduino, Real-time Monitoring*

1. Introduction



With the need to reduce carbon emissions, and the dwindling reserves of crude oil, liquid fuels derived from plant material biofuels are an attractive source of energy. Moreover, in comparison with other forms of renewable energy such as wind, tidal, and solar, liquid biofuels allow solar energy to be stored, and also to be used directly in existing engines and transport infrastructure. Currently, bio-ethanol from, for example, corn starch, sugar cane or sugar beet, and biodiesel from oil crops such as palm and oilseed rape, are the most widely available forms of biofuel. However, there are two major issues over the sustainability of these first-generation biofuels [1, 2]. Energy crisis is among the biggest problems, leading the world to be unsafe and non-peaceful. The demand is increasing day by day. The available resources are rapidly decreasing and indication is, soon will be vanished. In such situations, more attention is needed to be given towards renewable energy sources. Fossil fuels are used on a large scale in the world, but unsustainable because they increase CO₂ level and accumulate greenhouse gases which make the environment unhealthy. To keep the environment clean and maintain sustainability, renewable and environmentally friendly fuels are needed to be produced [3].

Microalgae are considered valuable sources for biofuels and bioproducts, but large-scale production demands significant water and nutrient inputs. Given the need for food security and the high value of microalgal biomass, using traditional water resources should prioritize food and feed applications over fuel [4]. Farms involved in crop production, aquaculture, and livestock are increasingly adopting Internet of Things (IoT) and artificial intelligence (AI) technologies to enhance their efficiency, boost productivity, and improve the quality of their products [5]. In recent years, algae-based biomass technologies have attracted growing interest because of their adaptability in generating useful agricultural inputs, including bio-stimulants and natural fertilizers [6]. Microalgal species using measurements of light absorption in each separate microalgal culture between 400 and 700 nm proposed by Havlik [7]. PH ranges from 6-10, Temperature ranges from 15-35 degree centigrade and CO₂ level is normal level or more concluded by Debowski [8]. Microalgae are gaining attention as a promising alternative energy source due to their high biomass yield, ability to grow in diverse environments, and rich oil content, making them a viable biofuel feedstock for scientists and fuel companies [9].

The urgent imperative to mitigate climate change and reduce dependence on fossil fuels has accelerated interest in renewable biofuels, with microalgae-derived biodiesel emerging as a highly promising third-generation alternative due to its rapid growth, high lipid productivity, and non-competition with food crops or arable land [10]. Microalgae such as *Chlorella*, *Scenedesmus*, and *Nannochloropsis* have been extensively studied for biodiesel production because they can accumulate lipid contents of over 60% (dry weight), significantly outperforming terrestrial biofuel crops [11]. The cultivation of microalgae in municipal, agricultural, or industrial wastewater not only reduces the need for freshwater and synthetic fertilizers but also contributes to effective removal of nitrogen, phosphorus, chemical oxygen demand (COD), and certain heavy metals all while producing biomass for biofuel conversion [12]. Advances in this integrated wastewater-algae biorefinery approach between 2022 and 2025 have boosted interest in circular economy models, where wastewater treatment and bioenergy production are mutually reinforcing [13]. Despite its potential, scaling up algal biodiesel systems faces challenges related to high harvesting and conversion costs, inconsistent yield under open cultivation systems, and complexities in nutrient and light control [14]. Machine learning workflows including neural networks, support vector machines, genetic algorithms, and random forests have been applied to optimize cultivation parameters such as nutrient supply, lighting regimes, and harvesting timing, thus improving overall biomass productivity [15]. The synergy of IoT sensors (for pH, dissolved oxygen, nutrient

concentration, light intensity, flow rate) with AI-based control algorithms allows autonomous regulation of algal reactors under highly dynamic wastewater conditions, enhancing process stability and lipid productivity [16]. Further, the use of microalgae-bacteria consortia in wastewater treatment has demonstrated notable improvements in nutrient removal and biomass yield, while also producing lipid-rich feedstock leveraged for biodiesel conversion [17]. While these technological advances show promise for decentralized, eco-friendly biofuel systems, a fully integrated platform combining wastewater phycoremediation, real-time IoT monitoring, edge-AI control, and biodiesel processing has not yet been realized in scalable prototypes [18].

Guimarães et al. [19] evaluated microalgae (*Chlorella vulgaris*, *Scenedesmus obliquus*) growth in wastewater and brackish waters in batch and continuous modes. They measured kinetic parameters, lipid content, nutrient removal efficiency, and performed cost analysis. Results showed biomass productivity up to $\sim 0.3 \text{ g L}^{-1} \text{ d}^{-1}$, lipid content around 20–25 %, with over 80 % removal of nitrogen and phosphorus; cost analysis suggested commercialization potential in regions where wastewater is abundant. Tan et al. [20] reported that microalgae are gaining considerable interest as a renewable source for biodiesel due to their high lipid content and rapid growth rate. They emphasized that selecting an appropriate cultivation method such as photobioreactors, open ponds, or hybrid systems is essential for optimizing biodiesel yield. Formighieri et al. [21] highlighted that the complex molecular structure of algal cells presents multiple avenues for utilization. Their research demonstrated that the lipid fraction especially triglycerides can be efficiently converted into biodiesel using established transesterification methods, while the residual biomass is suitable for fuel production through various biochemical and thermochemical conversion processes.

Gupta et al. [22] conducted a comprehensive review on microalgae cultivation using wastewater across multiple industries and urban waste streams with focus on bioremediation and co-product generation. They synthesized quantitative data confirming that wastewater systems not only remove >90 % of nitrogen and phosphorus but also generate feedstock for biofuels, nutraceuticals, and other bioproducts, although high cultivation costs remain a barrier without value-added product integration. Osman et al. [23] investigated two microalgal species (*Oocystis pusilla* and *Chlorococcus infusionum*) grown in 100 % municipal wastewater under controlled salinity stress. *O. pusilla* showed a 1.66-fold increase in dry biomass and elevated lipid content, while *C. infusionum* failed to survive. The study confirmed that untreated wastewater can outperform synthetic media in promoting lipid yield.

Yourassowsky et al. [24] developed a non-invasive method using digital holographic microscopy to quantify lipid droplets inside living *Phaeodactylum tricornutum* cells in real-time. They validated the technique against fluorescence imaging benchmarks and demonstrated accurate lipid volume estimation, enabling live monitoring of lipid accumulation during cultivation. Khan et al. [25] explored valorization of microalgae for urban wastewater treatment and converting biomass into biofertilizer. They grew local *Chlorella* strains in municipal wastewater and measured nutrient removal and biomass composition. Results indicated >90 % nutrient removal and significant protein/carbohydrate/lipid content suitable for biodiesel and biofertilizer applications. Jayaseelan et al. [26] provided a detailed review (used context through 2022) on integration of microalgal biofuel production with wastewater treatment, outlining pathways for simultaneous nutrient removal and biomass conversion. They highlighted that coupling wastewater remediation with biofuel production can reduce freshwater and fertilizer demand, although practical scaling remains a challenge.

Liao et al. [27] tested an IoT-edge computing architecture in wastewater-fed photobioreactors, processing sensor data locally to reduce communication latency. The system delivered more precise nutrient dosing and fostered stable algal growth, achieving higher lipid accumulation compared to conventional monitoring. Uguz et al. [28] proposed a real-time algal monitoring framework combining IoT-enabled imaging sensors with machine learning models. Using edge-computing and RGB cameras installed in photobioreactors, they processed color histograms via k-NN, decision tree, and random forest models to estimate biomass, nutrient levels, and pH in real time. The system demonstrated substantial reductions in manual sampling and enabled automated control of CO₂ injection, nutrient dosing, and lighting improving cultivation consistency and bioprocess efficiency. Wu et al. [29] integrated AI-driven computational fluid dynamics (CFD) and machine learning within a closed tubular photobioreactor equipped with IoT sensors. They optimized light intensity and temperature regimes, where continuous 24-hour lighting improved biomass productivity by ~7.2% compared to a 12-hour cycle. Growth prediction via XGBoost achieved R²≈0.9997, outperforming random forests (MSE drop from 0.0604 to 0.0063), demonstrating the benefit of precise light control in high-yield systems.

Hamid Nour et al. [30] reviewed modern strategies for extracting bioproducts from microalgae in integrated biorefineries, emphasizing wastewater as a nutrient source. They highlighted that combining advanced extraction techniques (e.g., enzymatic, supercritical CO₂) with digital tools like IoT and AI can boost lipid yields, cut energy use, and lower costs. The study supports using wastewater to promote circular bioeconomy models and recommends smart automation for future large-scale applications.

Table.1 Comparative Summary of Microalgae Cultivation for Biodiesel

Study	Species/System	Medium/Method	Key Parameters	Main Findings	Insights
Guimarães et al. [19]	<i>C. vulgaris</i> , <i>S. obliquus</i>	Wastewater & brackish; batch/continuous	Biomass, lipids, nutrient removal, cost	~0.3 g L ⁻¹ d ⁻¹ ; 20–25% lipids; >80% N & P removal	Cost-effective in wastewater areas
Tan et al. [20]	Microalgae (general)	Photobioreactors, ponds, hybrid	Cultivation strategies	High lipid & growth; system choice critical	System optimization key
Formighieri et al. [21]	Microalgae (general)	Photobioreactors, ponds, hybrid	Lipid utilization, conversion	Efficient triglyceride transesterification	Multipurpose biomass utilization
Gupta et al. [22]	Microalgae in wastewater	Urban/industrial wastewater	Nutrient removal, coproducts	>90% N & P removal; biofuel & nutraceutical feedstock	Value-added integration needed
Osman et al. [23]	<i>O. pusilla</i> , <i>C. infusioenum</i>	Municipal wastewater, salinity stress	Biomass, lipid yield	<i>O. pusilla</i> ↑1.66×; <i>C. infusioenum</i> failed	Untreated wastewater effective
Yourassowsky et al. [24]	<i>P. tricornutum</i>	Digital holographic microscopy	Lipid droplets (real-time)	Accurate, non-invasive lipid monitoring	Real-time lipid tracking

Khan et al. [25]	<i>Chlorella</i> (local)	Municipal wastewater	Nutrient removal, biomass profile	>90% N & P removal; biodiesel & biofertilizer	Dual-use potential
Jayaseelan et al. [26]	Microalgae (review)	Wastewater–biofuel integration	Nutrient removal, conversion	Reduces water/fertilizer demand; scaling issues	Integrated biorefineries
Liao et al. [27]	Wastewater photobioreactors	IoT-edge computing	Nutrient dosing, lipid accumulation	Stable growth; higher lipid yield	IoT improves control
Uguz et al. [28]	Photobioreactors	IoT + ML (RGB cameras)	Biomass, nutrients, pH	Automated control; reduced sampling	AI enhances efficiency
Wu et al. [29]	Closed tubular PBR	AI + CFD + IoT	Light/temperature optimization	24 h lighting ↑7.2%; XGBoost $R^2 \approx 0.9997$	AI improves productivity
Hamid Nour et al. [30]	Microalgae (review)	Wastewater; advanced extraction	Lipids, energy, automation	Enzymatic/supercritical CO ₂ extraction + AI reduces cost	Circular bioeconomy potential

Table 1 presents a comparative summary of microalgae cultivation systems for biodiesel production, highlighting various species, cultivation media, and methods. It outlines key parameters, major findings, and practical insights from different studies, providing a concise overview of the factors influencing biomass productivity and biodiesel potential.

2. Novelty Statement

This study presents a uniquely integrated and experimentally validated system for algal biodiesel production that addresses key limitations in existing research. While prior work has explored algae cultivation in wastewater, IoT-based monitoring, or biodiesel extraction separately, no existing study offers a complete, real-time, low-cost solution that combines all these components in a single operational platform. The proposed system uses untreated municipal wastewater as a nutrient medium, incorporates white LED lighting to enable continuous 24-hour algal growth, and employs an ESP32–Arduino-based IoT framework for real-time monitoring of critical parameters such as pH, temperature, CO₂ concentration, and water level. What distinguishes this work is its end-to-end experimental validation, demonstrating a 10% increase in biomass productivity, reduction in cultivation time by up to 8 days, and the production of 120 mL of biodiesel with a calorific value of 46.63 MJ/kg, exceeding that of conventional diesel. The system also undergoes rigorous testing including ignition and bomb calorimeter analysis to confirm fuel quality. This practical implementation bridges the gap between conceptual research and field-deployable solutions, offering a scalable, automated, and eco-friendly approach to biofuel generation. It positions itself as a promising model for decentralized energy production in resource-constrained or off-grid environments, where conventional fuel systems are neither sustainable nor accessible.

3. Materials and Methods

The methodology for biodiesel production from algae, encompassing system design, cultivation, monitoring, and extraction processes, is illustrated in Figure 1.

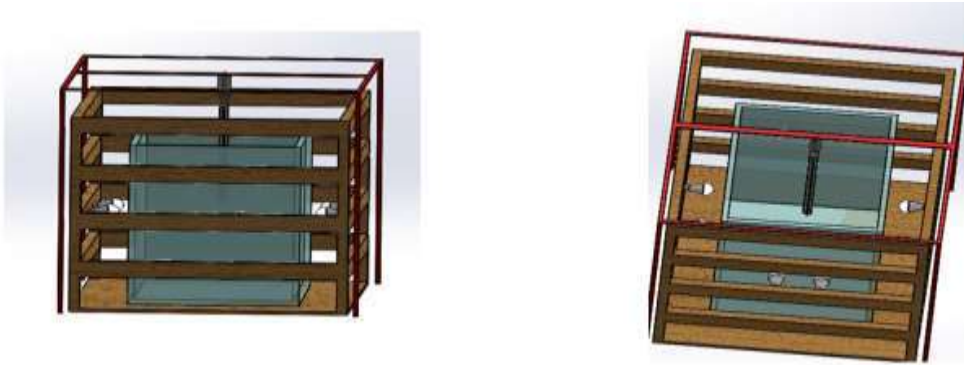


Figure 2. CAD model showing different views of the system for algae growth

3.2 Cultivation Setup

After setting up the system, water was added to the acrylic box to create a suitable environment for algae cultivation. A small amount (20 g) of algae was introduced, along with essential nutrients including 10 g of fish food (as a nitrogen source), 2 g of phosphate-based fertilizer, 2 g of potassium sulfate, 1 g of iron sulfate, and 1 g of magnesium sulfate. The system was left undisturbed for 12 days to allow algae growth. Continuous white light was provided using natural sunlight during the day and LED lights connected to a DC power source at night, ensuring optimal illumination for algae development, as shown in Figure 3.

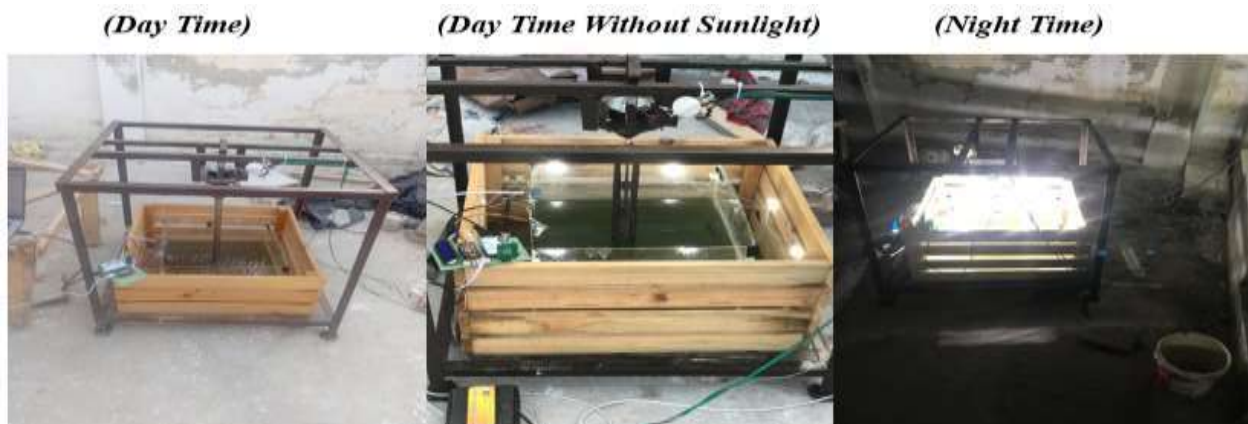


Figure 3. Algae cultivation during daytime with and without sunlight, and at nighttime

3.3 IoT and Sensor Integration

Real-time monitoring was implemented to ensure optimal algae growth conditions. Key parameters such as water level, carbon dioxide (CO₂) concentration, pH, and temperature were monitored using IoT sensors. The sensors pH sensor, CO₂ sensor, water level sensor, and temperature sensor were connected to a cloud-based system for continuous data collection. A mobile app interface allowed remote monitoring and management of the system, enabling timely adjustments and improved efficiency in algae cultivation, as shown in Figures 4 and 5.

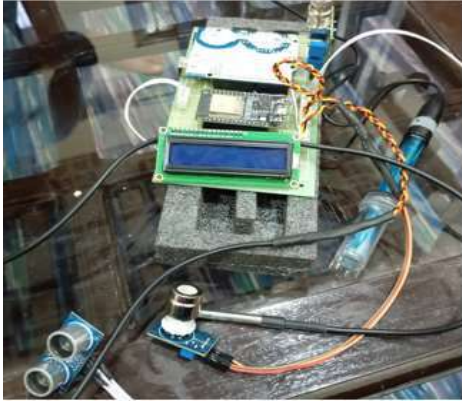


Figure 4. Circuit integration for monitoring



Figure 5. Circuit Board

3.4 Biodiesel Extraction Procedure

After cultivating algae in open ponds or photobioreactors, the algae biomass was separated from water. As algae typically exist in low concentrations (<1 g/L), a dewatering process was performed before lipid extraction. Harvested algae were placed on a cotton cloth to filter out contaminants, producing cleaner algal juice. The filtrate was then dried under direct sunlight for two days to evaporate water, yielding dry algae biomass, as shown in Figure 6.



Figure 6. *Algae harvesting*

The dried biomass (42 g) was ground to release lipids, which were extracted by soaking in n-hexane for 48 hours in a sealed container (Figure 7). The lipid-rich solution was filtered and separated using a separating funnel. For transesterification, methanol and sodium hydroxide (NaOH) were prepared in a 10:1 molar ratio and added to the lipid extract. The mixture was manually agitated for 90 minutes and left undisturbed for 24 hours. This process produced

two layers: biodiesel (upper layer) and glycerol (lower layer), as shown in Figure 8. The biodiesel was carefully filtered for further use.



Figure 7. Grinding process for biodiesel



Figure 8. Phase separation of biodiesel

4. Results and Discussion

4.1 Algae Growth Performance

After a 12-day cultivation period under continuous white light conditions (natural sunlight by day, LED at night), the algae mass increased from 20 g, as shown in Figure 9, to 42 g, as shown in Figure 10, resulting in a net biomass gain of 22 g. This indicates a 110% increase in algae biomass due to white lights at night. The environmental conditions and nutrient supplementation appeared adequate to support algae growth.

Algae Production yield and Efficiency:

Production rate = Total biomass produced / Volume of water in Liter*Number of days

Total mass produced = 42-20 = 22 gram.

Production rate = $22/20*100 = 110\%$



Figure 9. Algae initial amount



Figure 10. Final amount of Algae after 12 days

4.2 Biodiesel Yield Analysis

A yield of approximately 120 ml of biodiesel was obtained, as shown in Figure 11, indicating good conversion efficiency. Ignition and calorific value tests confirmed that the fuel meets basic standards, highlighting algae's potential as a sustainable biodiesel source.



Figure 11. Algae-Derived Biodiesel Production

Table.2 Biodiesel Yield vs Drying Time

Drying Time (Days)	Biodiesel Yield (ml)
1	40
2	90
3	120
4	128
5	130
6	131

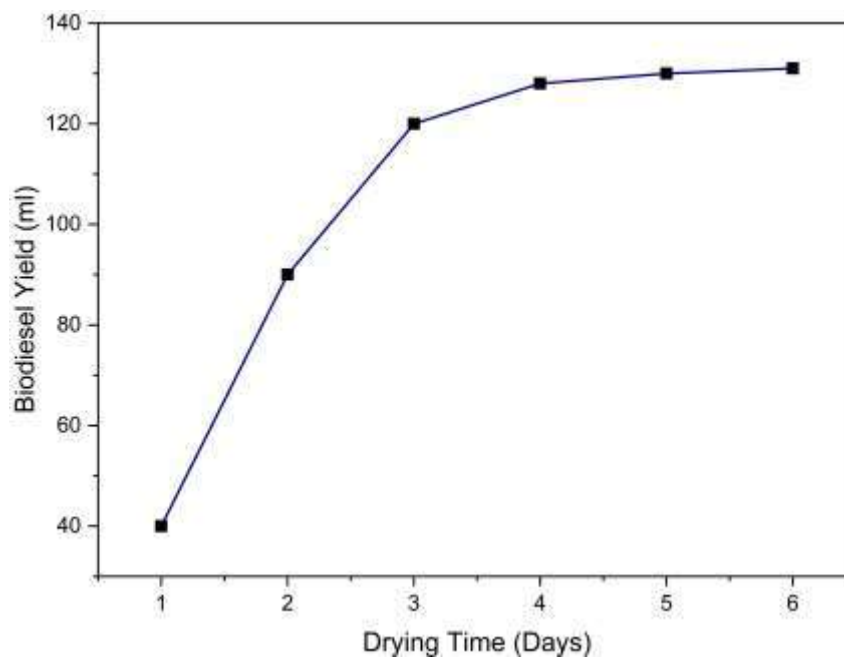


Figure 12. Biodiesel Yield vs Drying Time

The biodiesel yield, as presented in Table 2 and illustrated in Figure 12, exhibited a substantial increase with prolonged algae drying times. On the first day, the yield was 40 ml, indicating the presence of high residual moisture that hindered efficient lipid extraction. By the second day, the yield increased to 90 ml, reflecting significant improvement as moisture content reduced further. After three days, the yield reached 120 ml, approaching its optimal range. From the fourth to the sixth day, the yield only slightly increased to 128 ml, 130 ml, and finally plateaued at 131 ml, demonstrating that extended drying beyond three days results in marginal gains. This trend highlights that while proper drying is essential for maximizing oil recovery, excessively long drying durations offer minimal additional benefits.

4.3 Fuel Quality Verification

4.3.1 Test 1

An ignition test, as shown in Figure 13, was conducted to verify the quality of the produced biodiesel. A small amount was placed on a nonflammable surface and ignited after reaching the required temperature. The flame, color, and smoke were observed, and clean combustion indicated good purity. A flue gas analyzer may be used if further verification is needed.



Figure 13. Ignition test

Table. 3 Bomb Calorimeter Test 1 Results (UET Mardan)



Figure 14. Initial Temperature



Figure 15. Final Temperature

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Parameter	Value	Unit
Mass of diesel	0.6	g
Mass of nichrome wire	0.05	g
Mass of cotton thread	0.085	g
Length of cotton thread	100	mm
Mass of water in calorific vessel	2	kg
Initial temperature	18.4	°C
Final temperature	21.3	°C
Net temperature rise	2.9	°C
Cotton fuse heat release (Q_c)	4180 cal/g (1796.6)	J/g
Nichrome wire heat release (Q_w)	0.335×10^{-3} cal/g (1402.2)	J/g
Gross calorific value (q)	46,630	kJ/kg
Calorific value	46.63	MJ/kg

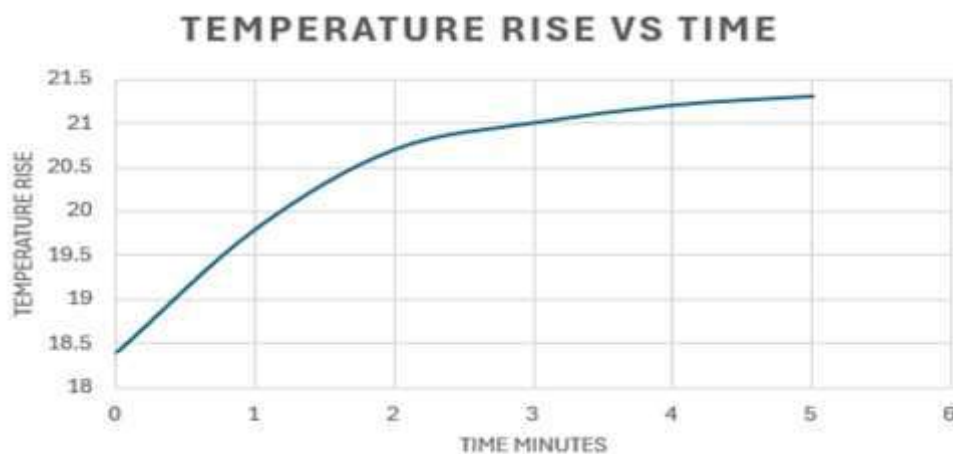


Figure 16. Temperature Vs Time Chart

The results of Bomb Calorimeter Test 1, conducted at UET Mardan, are summarized in Table 3. The initial temperature of the calorific vessel was recorded at 18.4 °C (Figure 14) and increased to 21.3 °C (Figure 15) after combustion, giving a net rise of 2.9 °C. The temperature time relationship during the experiment is illustrated in Figure 16, showing a steady and measurable increase in temperature. Using the recorded parameters and heat contributions from the cotton fuse and nichrome wire, the gross calorific value of the algae-derived biodiesel was calculated as 46,630 kJ/kg, corresponding to a calorific value of 46.63 MJ/kg. This high energy

content is comparable to conventional diesel fuels, confirming the potential of algae-based biodiesel as a viable renewable energy source.

4.3.2 Test 2

The second calorific value test, conducted at the National Cleaner Production Center Foundation in Islamabad (Figure 17), reported a net calorific value of 45.16 MJ/kg.

National Cleaner Production Center Foundation
 Registered under Section 42 of the Companies Ordinance, 1984
Commercial Sample Test Report

Sample Id:	C-UETM-1	Customer:	UET Mardan
Date Received:	26-MAY-25	Date Reported:	02-JUN-25
Product:	Bio Diesel	Source:	Student (Ammar Zaib) UET Mardan
S.No.	Test Description	Test Method	Test Result
1	Calorific Value Gross, BTU/Lb	ASTM D4809	19416

Remarks: This report shall not be reproduced / made part of any investigation / inquiry / or used for any litigation purpose. This report is based solely on the sample(s) tested. Sampling responsibility lies with customer.

Prepared By: [Signature]
 Issued By: [Signature]
 End of Test Report

Figure 17. Bomb Calorimeter Test 2 at National Cleaner Production Center Foundation

The net calorific value from this report is 45.16 MJ/Kg

Table. 4 Calorific Value comparison

Sample No.	UET Mardan (Bomb Calorimeter) (MJ/kg)	NCPC Foundation (ASTM D4809) (MJ/kg)	Diesel Standard (MJ/kg)
S1	46.58	45.12	42.4
S2	46.64	45.18	42.9
S3	46.66	45.2	43.3
S4	46.61	45.14	43.8
S5	46.65	45.17	44.1

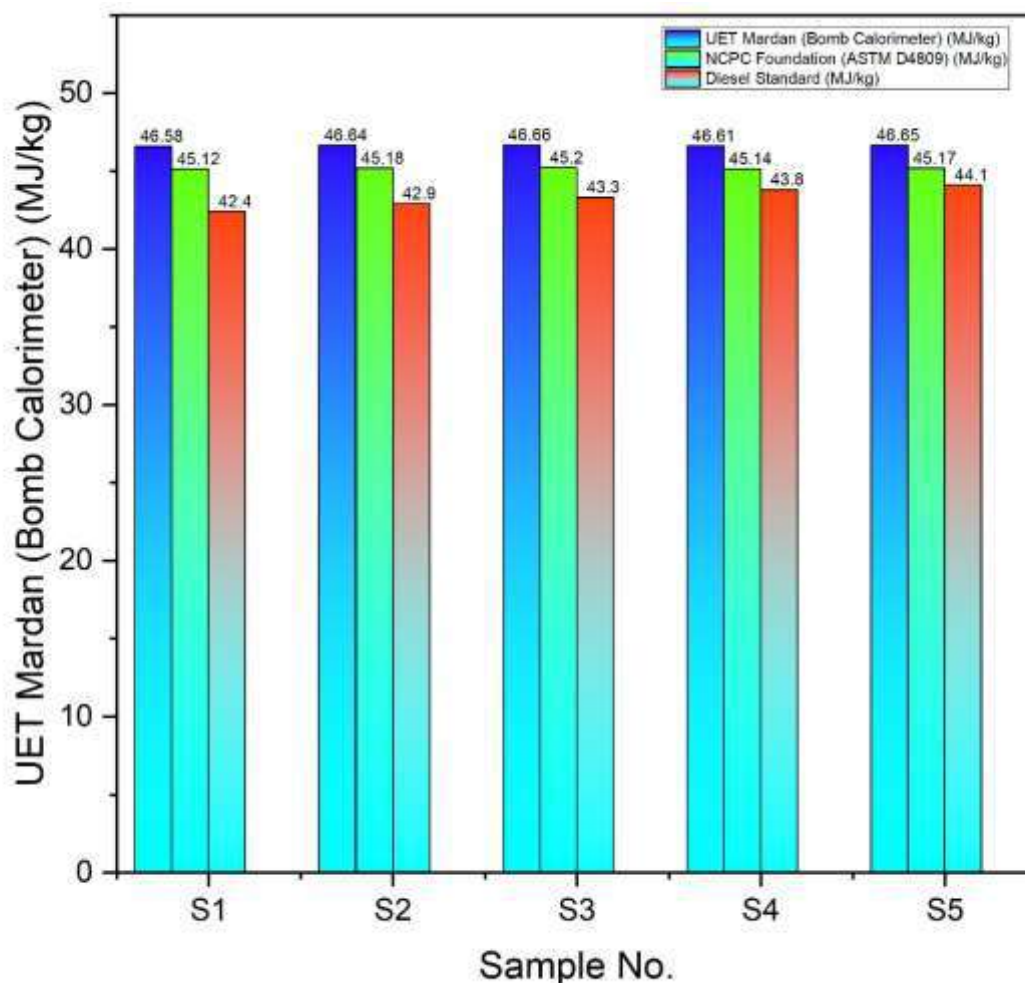


Figure 18. Chart showing different calorific values

As presented in Table 4 and illustrated in Figure 18, the calorific value of the algae-based biodiesel exhibited a consistent performance across five samples, with values ranging from 46.58 to 46.66 MJ/kg in the Bomb Calorimeter test at UET Mardan and from 45.12 to 45.20 MJ/kg in the ASTM D4809 test conducted at the NCPD Foundation. Both sets of measurements are higher than the typical diesel range of 42.0–44.5 MJ/kg, demonstrating a comparatively superior energy yield. The minor variation between the two testing methods is attributed to their different measurement principles, where Bomb Calorimetry provides the gross calorific value and ASTM D4809 determines the net calorific value. These findings confirm the high energy potential and practical feasibility of algae-based biodiesel as a sustainable alternative to conventional diesel.

4.5 IoT Monitoring Result

The IoT-based monitoring system efficiently collected real-time data from sensors measuring pH, temperature, CO₂, and water level. Data was transmitted to the cloud via MQTT and displayed on a user-friendly app interface using Firebase, as shown in Figure 19. The dashboard, shown in Figure 20, displayed live values with color-coded alerts for unsafe conditions (e.g., pH > 8.5 or temperature > 35 °C), while notifications and historical logs enabled timely actions and trend

analysis. This system ensured accurate monitoring and better control of algae cultivation conditions.



Figure 19. App Interphase

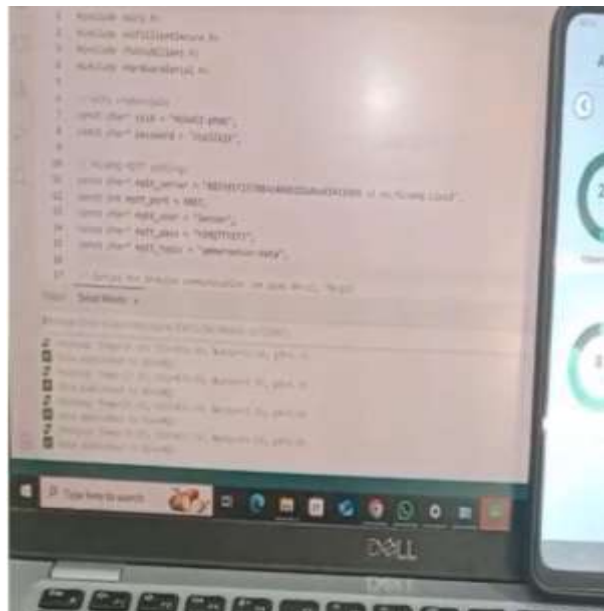


Figure 20. Display screen for monitoring

5. Conclusion

This study successfully demonstrated the production of high-quality biodiesel from algae using a cost-effective and sustainable process. Experimental results and quantified performance metrics confirm its strong potential as a renewable fuel source.

- Algae biomass increased from **20 g to 42 g** over **12 days** under continuous white light (sunlight by day, LED at night), achieving a **110%** growth rate and a net gain of **22 g**.
- Biodiesel yield improved with drying time, producing **40 ml** after **1 day**, **90 ml** after 2 days, and 120 ml after 3 days from 40 g of dried algae.
- Calorific values of 46.63 MJ/kg (Bomb Calorimeter, UET Mardan) and 45.16 MJ/kg (ASTM D4809, NCPC Foundation) exceeded the conventional diesel range of 42.0–44.5 MJ/kg.
- Ignition tests confirmed clean combustion with minimal smoke, indicating high fuel purity.
- An IoT-based monitoring system provided real-time tracking of pH, temperature, CO₂, and water level, with automated alerts for unsafe conditions (e.g., pH > 8.5, temperature > 35 °C) and historical logging for process optimization.

Overall, the combination of optimized biodiesel production and intelligent monitoring establishes algae-derived biodiesel as a high-energy, clean-burning, and scalable alternative to fossil fuels, supporting global clean energy and sustainability goals.

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