IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 1 (2026) 273-284
https://publisher.uthm.edu.my/ojs/index.php/ijie

Development of Oil Palm Based Biomass Technology for Renewable Energy Harvesting

Azuwien Aida Bohari[1]*, Emier Nurman Hazeem[1], Muhammad Rusydi Muhammad Razif[1], Khalid Aboubakr Hasan Mousay[2], Mohd Nizam Mohd Talib[3], Mohd Abdul Talib Mat Yusoh[4], Mohd Norazysyam Azman[5]

[1] *Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, KM1 Jalan Panchor, 84600 Pagoh, MALAYSIA*
[2] *Technical College of Civil Aviation and Meteorology Esbea, LIBYA*
[3] *Kolej Komuniti Kluang, Taman Delima, 86000 Kluang Johor, MALAYSIA*
[4] *College of Engineering, Universiti Teknologi MARA, 40450, Shah Alam, Selangor, MALAYSIA*
[5] *Victory Enghoe Plantations Sdn. Bhd., Southern Malay Palm Oil Mill, Miles 41, Jln Johor Bahru 86200 Simpang Renggam, Kluang, Johor, MALAYSIA*

*Corresponding Author: azuwien@uthm.edu.my
DOI: https://doi.org/10.30880/ijie.2026.18.01.020

Article Info

Received: 2 January 2026
Accepted: 30 March 2026
Available online: 20 April 2026

Keywords

Oil palm, renewable energy, sustainability

Abstract

Oil palm biomass presents considerable potential as a renewable energy source for sustainable agricultural applications. This study develops and evaluates an oil palm biomass-based renewable energy system integrated with an automated irrigation mechanism. Biomass pellets were combusted to generate steam that drives a turbine-dynamo system for electricity production. Experimental results show that the series configuration of two dynamo motors produced the highest output voltage of 5.72 V at 380.36 RPM under no-load conditions and 5.22 V under load, demonstrating superior energy conversion performance compared to single and parallel configurations. The automated irrigation system successfully activated the water pump when soil moisture dropped below 30 percent, ensuring efficient water management and reduced wastage. The system operated stably using a lithium-ion battery for energy storage and supply. Overall, the findings confirm that oil palm biomass pellets are a viable small-scale renewable energy source capable of supporting precision agriculture applications, with strong potential for scalability in sustainable agricultural development.

1. Introduction

A variety of environmental, financial, and energy-related factors have contributed to a recent increase in interest regarding the utilization of biomass sourced from oil palm for renewable energy production. Castillo (2007, p. 7) highlights that the oil palm industry ranks among the largest agricultural sectors globally, with significant operations in Southeast Asia, parts of Africa, and Latin America. The production of palm oil generates substantial quantities of biomass waste, including empty fruit bunches (EFBs), palm kernel shells (PKS), and mesocarp fibers. Traditionally, these by products have been underutilized or regarded as waste. In the past, such waste was either incinerated outdoors, leading to air pollution and associated health risks, or left to decompose in the fields, which contributed to methane emissions and environmental degradation (Yusuf, 2006, p.5). Nevertheless, there is a growing interest in converting oil palm biomass into renewable energy, driven by environmental concerns, the urgent need to diversify energy sources, and the impacts of climate change.

Biomass derived from oil palm presents numerous inherent advantages for energy production. As a high-yielding, perennial crop, its plentiful availability ensures a reliable and steady supply. Serving as a renewable energy source, these byproducts also reduce dependence on fossil fuels, thereby decreasing greenhouse gas emissions and contributing to the battle against climate change. Moreover, the transformation of biomass into energy generates economic advantages by creating jobs and additional income, particularly in rural areas where oil palm plantations are prevalent. There are various techniques for converting palm biomass into energy, including gasification, pyrolysis, and combustion. Each method possesses distinct advantages and disadvantages based on factors such as feedstock properties, energy efficiency, and environmental impact. Additionally, advancements in co-firing, a technique that involves blending biomass with traditional fuels in power generation facilities, have enhanced the feasibility of integrating palm biomass into current energy systems.

2. Literature Reviews

Biomass encompasses organic materials such as forestry waste, agricultural residues, and energy crops, serving as a flexible and sustainable renewable energy source. Among these, oil palm biomass is particularly notable due to its extensive availability and considerable energy potential. The underutilization of byproducts from oil palm production, including empty fruit bunches (EFBs), palm kernel shells (PKS), and mesocarp fibers, contributes to methane emissions and air pollution. Converting these wastes into energy not only addresses waste management issues but also mitigates broader environmental challenges, thereby positioning oil palm biomass as a significant renewable resource (Ayer & Balart, 2005; Yusuf, 2006).

A range of technologies are available to convert oil palm biomass into usable energy. Combustion, the most direct method, involves burning biomass to generate heat and electricity, with modern systems offering improved efficiency and lower emissions (Nazario-Nevada, 2021). Gasification transforms biomass into syngas a flexible fuel through controlled heating in a low-oxygen environment (Heinrich, 2007). Pyrolysis, another thermochemical process, breaks down biomass into bio-oil, syngas, and biochar, enabling both energy generation and the recovery of valuable byproducts (Siwal, 2022). Emerging technologies such as co-firing with fossil fuels, combined heat and power (CHP) systems, and the integration of moisture sensors are enhancing overall system efficiency while minimizing emissions. Additionally, byproducts like biochar offer agronomic benefits, improving soil health, nutrient retention, and water-holding capacity (Kim, 2017). Nevertheless, the large-scale deployment of oil palm biomass faces several challenges, including high pre-processing costs, logistical constraints, and the environmental impacts of extensive palm cultivation (Yusuf, 2006). However, advancements in microcontroller-based systems, sensor technologies, and biomass boiler designs are contributing to greater operational efficiency.

Compared to other biomass sources, oil palm biomass offers higher energy density and consistent, year-round availability. Its development is further supported by evolving technologies and supportive policy frameworks (Castillo, 2007). Beyond its environmental benefits, palm oil biomass also presents socio-economic opportunities, particularly in rural areas where oil palm cultivation is prevalent. By optimizing energy conversion technologies and embracing innovative practices, oil palm biomass can play a pivotal role in advancing a more sustainable and resilient energy future.

2.1 Comparison with Previous Researcher Work

Oil palm biomass has significant potential as a decentralized renewable energy source for sustainable agricultural systems. This study presents the design, development, and experimental evaluation of a small-scale oil palm biomass-based energy harvesting system integrated with an automated irrigation control mechanism. Biomass pellets were combusted to generate steam that drives a turbine coupled with a dynamo for electrical power generation. Experimental findings indicate that the series configuration of two dynamo motors achieved the highest performance, producing 5.72 V at 380.36 RPM under no-load conditions and 5.22 V under load, demonstrating improved voltage stability and energy conversion efficiency compared to single and parallel configurations.

The irrigation subsystem, controlled by an Arduino microcontroller, automatically activated the water pump when soil moisture levels dropped below 30 percent, ensuring precise and efficient water utilization. In contrast to previous studies that predominantly emphasized large-scale biomass power plants or standalone irrigation automation, this work demonstrates an integrated micro-scale biomass-to-electricity and precision irrigation framework within a unified system architecture. The prototype exhibited stable energy storage performance using a lithium-ion battery and consistent operational reliability. These results validate the technical feasibility of oil palm biomass pellets as a practical energy source for precision agriculture and highlight the scalability potential of decentralized biomass-powered smart irrigation systems in oil palm-producing regions.

3. Methodology

This system utilizes renewable energy derived from oil palm biomass pellets to produce electrical power while simultaneously supporting automated plant irrigation. The biomass pellets are manufactured from oil palm agricultural waste, which would otherwise be discarded, making the process both environmentally friendly and sustainable. When these pellets are combusted, they generate a significant amount of heat energy. This heat is used to boil water inside a pressure cooker, producing high-pressure steam as the water temperature increases. The generated steam is directed toward a turbine, where the kinetic energy of the moving steam is converted into mechanical energy. As the turbine rotates, it drives a dynamo motor that converts the mechanical energy into electrical energy. This electrical energy is not used immediately but is stored in a lithium-ion battery, allowing the system to operate even when the biomass combustion process is not active. The stored energy ensures a stable and continuous power supply for all system components.

An Arduino Uno microcontroller serves as the central control unit of the system. It is powered by the energy stored in the lithium-ion battery and continuously monitors environmental conditions through connected sensors. A soil moisture sensor is embedded in the soil near the plants to measure the water content in real time. The sensor sends analogue data to the Arduino, which processes the information and compares it to a predefined moisture threshold. When the soil moisture level drops below the required value, the Arduino automatically activates a water pump to irrigate the plants. This automated response ensures that plants receive adequate water precisely when needed, reducing water wastage and eliminating the need for constant human supervision. At the same time, an alarm buzzer is triggered to alert users that the soil moisture level has fallen below the optimal range, providing an additional layer of monitoring and awareness.

For user interaction and system monitoring, an LCD panel is integrated into the setup. The LCD continuously displays real-time soil moisture readings and system status, enabling users to easily observe environmental conditions and system performance. This visual feedback helps users make informed decisions regarding plant care and energy usage.

Overall, this system demonstrates an effective integration of renewable energy generation and automated irrigation technology. By utilizing oil palm biomass waste as a fuel source and combining it with sensor-based control and energy storage, the system promotes sustainable agricultural practices. It enhances plant health through precise irrigation, reduces manual labour, optimizes water consumption, and contributes to environmentally responsible energy utilization, making it a promising solution for precision agriculture and sustainable energy applications.

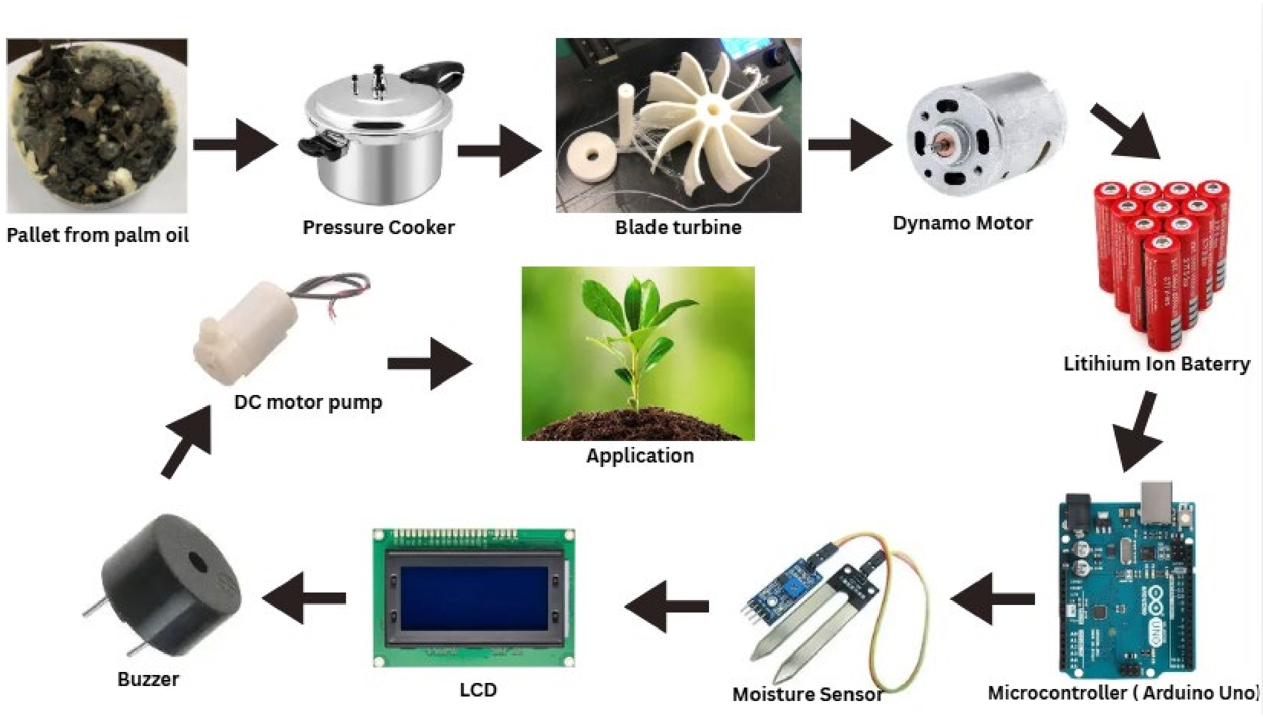


Fig. 1 *System diagram*

The system diagram illustrating a renewable energy-driven automated irrigation system is presented in Figure 1. The process initiates with steam produced by the combustion of biomass derived from oil palm, which drives a turbine connected to a dynamo. The dynamo converts the thermal energy into electrical energy, which is subsequently stored in a lithium-ion battery. An Arduino Uno microcontroller, serving as the central control unit of the system, operates on this stored energy. Through a connected sensor, the Arduino consistently monitors the soil's moisture levels. When the sensor detects dry soil, the Arduino activates a motor pump to commence irrigation. If the soil moisture is adequate, the system remains in monitoring mode without engaging the pump. Once the irrigation process is complete, the system automatically deactivates the pump. By integrating renewable energy sources and automating irrigation based on real-time soil conditions, this design promotes efficient water utilization.

3.1 Biomass and Applications System

Pellets derived from oil palm biomass, which is a sustainable energy source created from waste generated by the oil palm industry, initiate the process. In a pressure cooker, the heat generated from the combustion of these pellets produces steam. This high pressure steam is then utilized to rotate a turbine. The resulting motion drives a dynamo motor, which converts mechanical energy into electrical energy. A lithium-ion battery functions as the power reservoir for the system, storing the generated electricity.

An Arduino Uno microcontroller acts as the primary control unit and is powered by the stored energy. It receives input from a soil moisture sensor that continuously monitors the moisture level of the soil. For ease of monitoring, the real time data from the sensor is displayed on an LCD panel. When the soil moisture falls below a predetermined threshold, the sensor notifies the Arduino, which activates a motor pump to irrigate the plants. Simultaneously, a buzzer is triggered to alert users about the low moisture condition.

The pump ensures that water is delivered directly to the plants, maintaining optimal moisture levels for robust and healthy growth. This technology effectively integrates automated irrigation with renewable energy. While the Arduino-based automation manages the irrigation process through precise sensor input, motor control, and user notifications, the oil palm biomass serves as a sustainable energy source. This system not only promotes ongoing plant health but also minimizes manual labour and enhances efficient water usage. The corresponding block diagram of the system is illustrated in Figure 2.

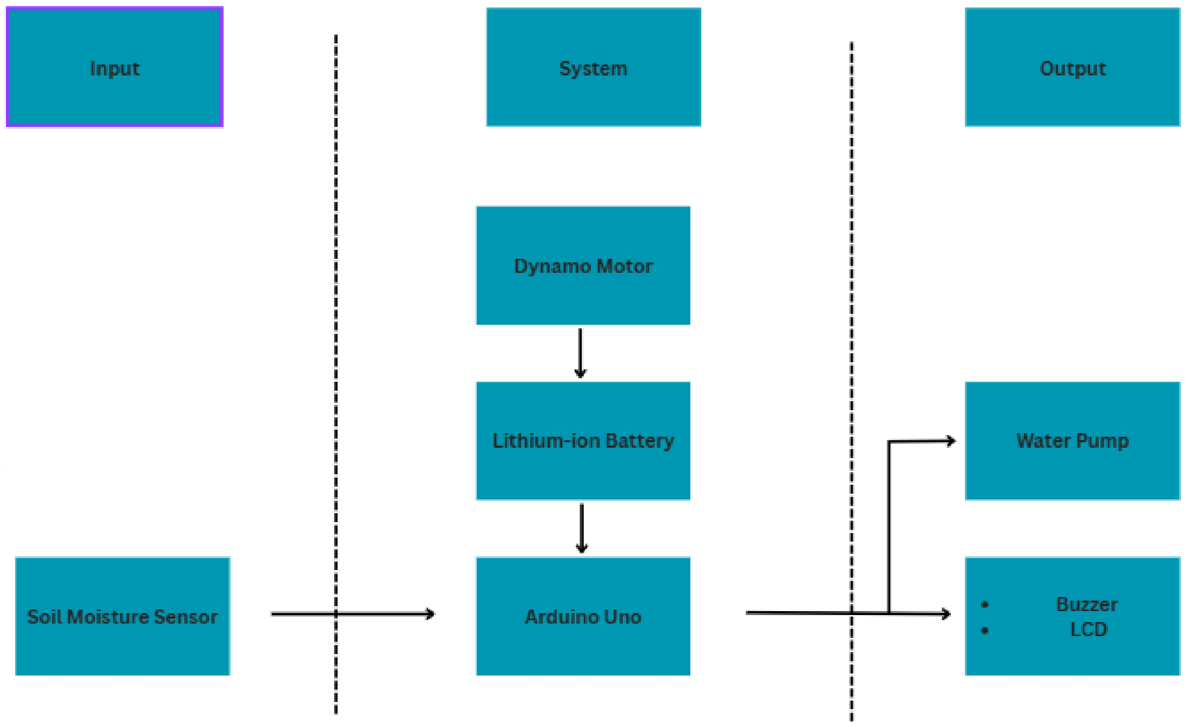


Fig. 2 *Project block diagram*

Arduino utilizes the energy stored in lithium-ion batteries to activate a motor pump that waters the plants when the soil moisture levels fall below a specified threshold. Simultaneously, a buzzer is triggered to alert users about the low moisture condition. The pump delivers water directly to the plants, ensuring optimal soil moisture levels and fostering healthy plant growth. This technology effectively merges automated irrigation management with renewable energy utilization. By integrating sensors, a motor pump, and an alarm system, the Arduino-based control unit automates the irrigation process, while oil palm biomass serves as a sustainable energy source for power generation. With precise moisture monitoring and responsive actions, this setup enhances consistent plant care, minimizes manual labour, and enables efficient water management. Figure 3 illustrates the system flowchart that depicts this operational sequence.

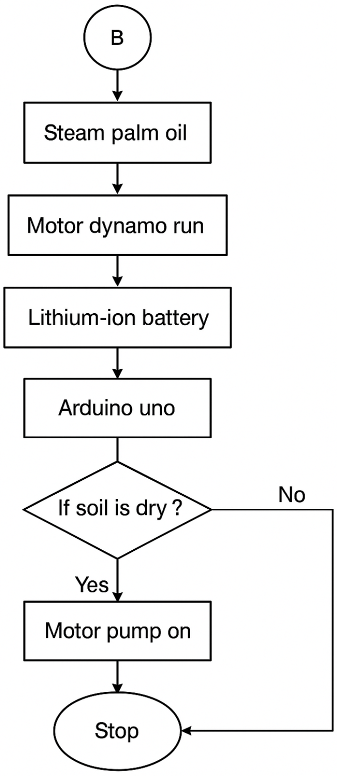


Fig. 3 *Flowchart system*

4. Results and Discussion

The effective functioning of the turbine and dynamo motors in generating power demonstrated the effectiveness of oil palm biomass pellets as a renewable energy source. The energy produced was reliably stored in the lithium-ion battery, which acted as a consistent power supply for the system. The Arduino based control system proficiently managed the irrigation process by activating the motor pump when the soil moisture dropped below the set threshold, while the soil moisture sensor delivered accurate, real-time information. This automatic response facilitated healthy plant growth, reduced water wastage, and ensured optimal soil moisture levels. The findings underscore the potential integration of precision agriculture with sustainable energy production. In modern agricultural practices, the efficiency of the energy conversion system and the intelligent irrigation control present promising opportunities for resource conservation and environmental sustainability.

4.1 Actual Prototype

This initiative promotes agricultural management and the generation of renewable energy by integrating automation with biomass technology derived from oil palm. In a pressure cooker fuelled by biomass pellets produced from oil palm, steam is generated. This steam drives a turbine connected to a dynamo motor to generate energy. The electrical energy is stored in lithium ion batteries and regulated through a DC-DC converter to supply power to an Arduino-based control system. The Arduino continuously monitors soil moisture levels and activates a water pump when the soil is dry, while also triggering a buzzer to alert the user. This self-sustaining system effectively repurposes oil palm biomass for energy production while automating irrigation, promoting both resource efficiency and environmental sustainability. Figure 4 shows the actual working prototype of the system.

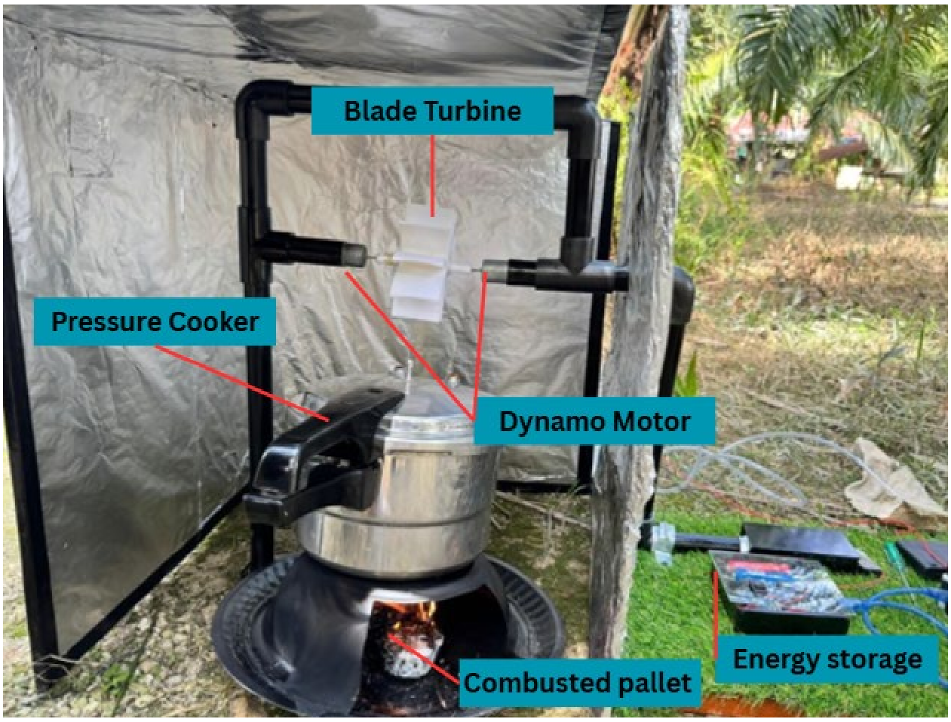


Fig. 4 *Project actual prototype*

4.2 Testing the Motor Without Load

This project focuses on the development of oil palm-based biomass technology for efficient renewable energy harvesting. Various dynamo motor configurations were tested namely, a single dynamo motor, two dynamo motors in parallel, and two in series. Among these, the series configuration demonstrated the most effective performance. The two dynamo motors connected in series produced the highest output voltage of 5.72 V and a rotational speed of 380.36 RPM, making it the most suitable for efficient energy storage and long-term operation. In comparison, the single motor setup, while straightforward, generated only 3.26 V and 410.97 RPM, which is inadequate for powering larger systems. The parallel configuration improved torque and reduced mechanical stress on the motors but resulted in a lower voltage output of 2.95 V, limiting its efficiency for energy storage applications.

The series configuration successfully combines higher voltage output with stable performance, ensuring optimal utilization of energy harvested from oil palm biomass. In conclusion, connecting two dynamo motors in series significantly enhances energy conversion efficiency and supports the goal of sustainable renewable energy harvesting. Figure 5 illustrates the motor performance graph under no-load conditions.

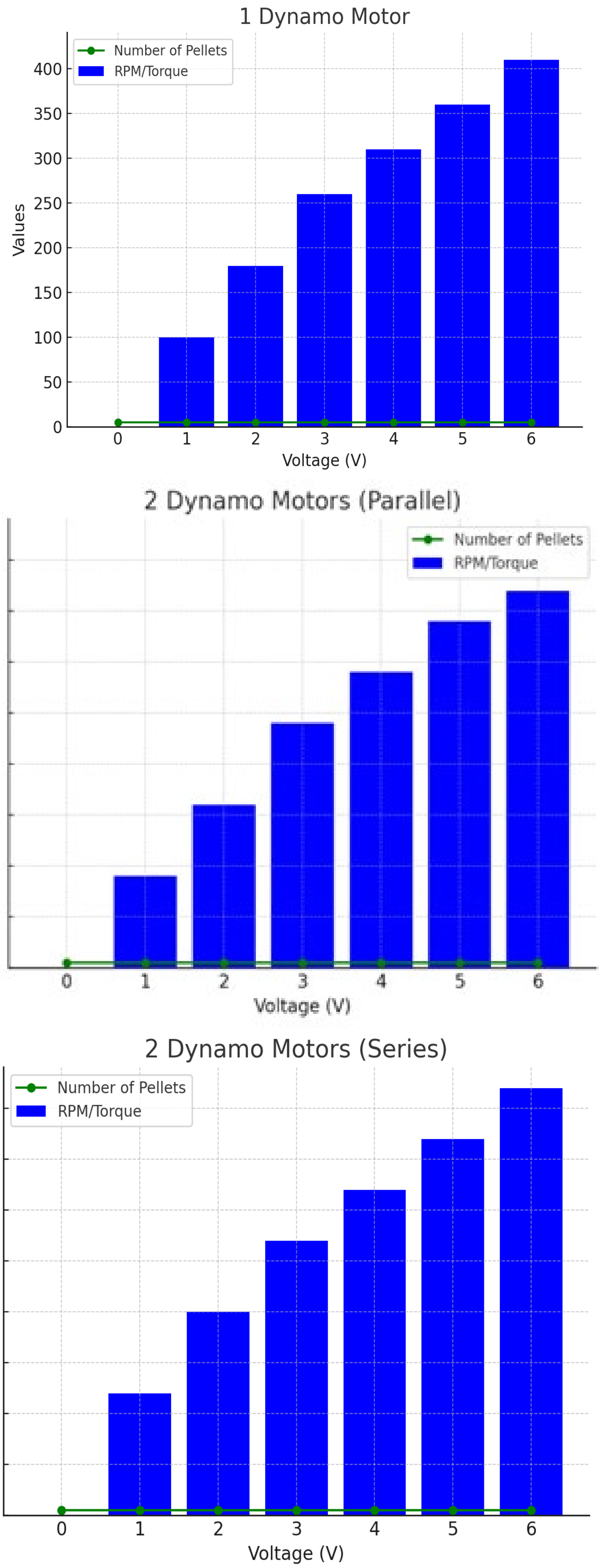


Fig. 5 *The graph of testing the motor without load*

4.3 Testing the Motor with Load

When comparing motor performance under load and no-load conditions, it is evident that load significantly affects the current-voltage relationship across all configurations. For the single dynamo motor setup, torque (RPM) increases rapidly without load, reaching 410.97 RPM at 3.26 V. Under load, the same torque is achieved at a lower voltage of 2.87 V, indicating the motor operates less efficiently and must work harder when a load is applied. In the case of the two dynamo motors connected in parallel, the impact of the load is more pronounced. Without load, the motors achieve 380.36 RPM at 2.95 V. However, under load, this torque is only reached at 2.61 V. The torque increases more gradually with voltage underload, suggesting the motors struggle to maintain performance.

The configuration with two dynamo motors in series demonstrates the highest efficiency. Without load, it achieves 380.36 RPM at 5.72 V, while under load, the same torque is obtained at 5.22 V. This minimal drop in voltage highlights better voltage sharing and improved efficiency. Overall, load conditions reduce efficiency in all setups. However, the series configuration proves to be the most resilient and efficient underload, making it the most suitable choice for renewable energy harvesting applications. Tables 1-3 present the detailed testing results.

Table 1 *Testing with 1 dynamo motor with load*

Voltage,V (max)	Current,A (max)	RPM / Tourque (max)	Time (second)	Number of Pallets
0	0	0	900	3
0.89	0	117.32	900	6
1.58	0	149.91	900	9
2.19	0.01	253.13	900	12
2.87	0.01	410.97	900	15

Table 2 *Testing with 2 dynamo motor with load (parallel)*

Voltage,V (max)	Current,A (max)	RPM / Tourque (max)	Time (second)	Number of Pallets
0	0	0	900	3
0.66	0	103.29	900	6
1.27	0.01	136.71	900	9
2.06	0.01	231.72	900	12
2.61	0.02	380.36	900	15

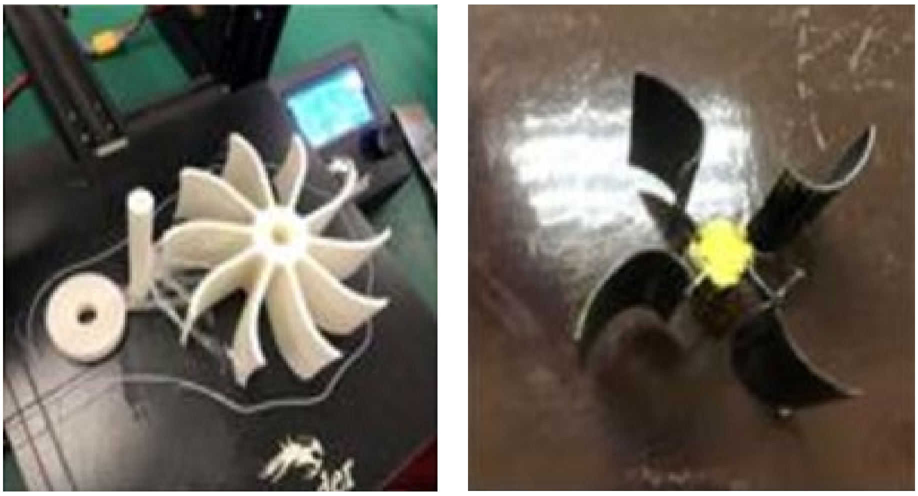
Table 3 *Testing with 2 dynamo motor with load (series)*

Voltage,V (max)	Current,A (max)	RPM / Tourque (max)	Time (second)	Number of Pallets
0	0	0	900	3
1.03	0	103.29	900	6
2.35	0	136.71	900	9
4.19	0.01	231.72	900	12
5.22	0.02	380.36	900	15

4.4 Testing Using Different Blade

The comparison of the two turbine blade designs reveals significant differences in performance, materials, and overall suitability for energy generation applications. The 10 curved fan blades of the 3D-printed ABS blade are engineered to optimize the capture of steam energy. Its aerodynamic shape and increased blade count make it particularly effective for tasks such as charging lithium-ion batteries, as they provide enhanced torque and power.

However, this design experiences greater air resistance, resulting in a slower rotation speed and a heavier weight. Additionally, the complexity of the 3D printing process contributes to higher manufacturing costs.



(a) (b)

Fig. 6 *The types of blades (a) 3D printing using abs material; (b) Plastic material*

Despite these limitations, the ABS blade excels in energy-intensive applications due to its impressive performance under stress. However, it is important to note that ABS can deform over time when exposed to high temperatures, leading to moderate durability. In contrast, the plastic blade, which consists of four flat fan blades, features a lighter and simpler design that allows for quicker rotation. Unfortunately, this results in reduced torque and power output, making it less effective for high-demand energy applications. It is more suitable for low-cost or lightweight uses, as it is cheaper and easier to manufacture through conventional plastic moulding techniques. Nevertheless, the plastic blade is less durable and struggles under pressure, increasing the likelihood of breakage in challenging conditions.

In conclusion, the 3D-printed ABS blade with 10 curved blades stands out as the superior choice for steam turbine projects aimed at energy harvesting, especially when consistent and reliable performance is essential. Despite its higher cost and complexity, its ability to generate strong torque and sustain load conditions makes it a more effective solution. Figure 6 illustrates both blade designs.

4.5 Testing the Soil Moisture Sensor

During the operation of the soil moisture monitoring system, the water pump is automatically activated when the soil moisture level drops below 30%, as detected by the sensor. For example, on 19 November 2024 at 8:00 AM, the sensor recorded a moisture level of 26%, prompting the system to activate both the pump and buzzer to ensure the plants received sufficient water. The LCD screen displayed real-time information such as “Pump: ON” along with the current moisture level, while the serial monitors logged data entries like “Moisture: 26%, Pump Activated,” confirming the system’s responsive action. This testing demonstrates the system’s effectiveness in managing irrigation automatically based on real-time soil conditions. Figure 7 shows the soil moisture sensor in testing.

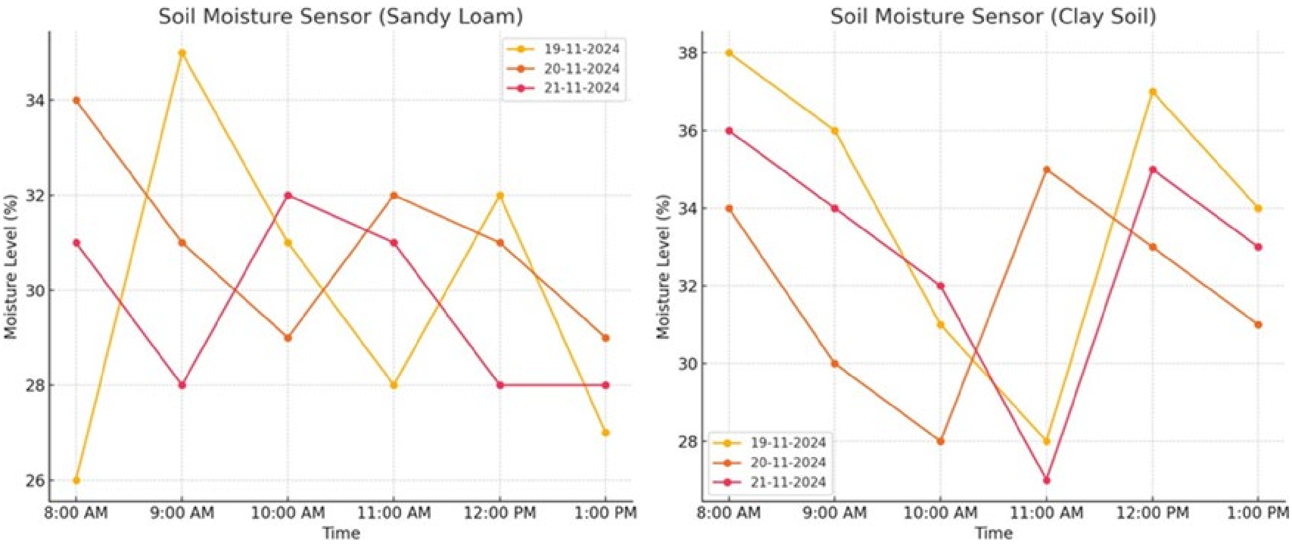


Fig. 7 *Testing the soil moistures sensor*

Soil type plays a crucial role in determining the frequency and efficiency of irrigation. For instance, sandy loam soils, which have larger particles and low water-holding capacity, allow water to drain quickly. As a result, crops or plants grown in sandy loam require more frequent but smaller amounts of watering to prevent water stress. On the other hand, clay soils have much finer particles and higher water retention. The water absorbs slowly but hold onto it for longer periods, reducing the need for frequent irrigation. This makes clay soil particularly advantageous in water-scarce regions, as it supports more efficient water use and reduces the risk of drought stress on crops. Understanding these differences is critical when designing or managing an irrigation system. By aligning the watering schedule with the specific characteristics of the soil, it’s possible to optimize water usage, avoid overwatering or underwatering, and improve plant health and yield. Moreover, this approach contributes to sustainable water management in agriculture or landscaping.

Fig. 8 *The LCD screen indicates pump activation by displaying “ON”*

In the irrigation system illustrated, Figure 8 displays the LCD screen showing "Pump: ON," indicating that the system is actively delivering water to the soil. This real-time feedback allows users to monitor and adjust irrigation activity based on soil type, weather conditions, and plant needs, further enhancing the system's effectiveness and reliability.

5. Conclusion

In conclusion, this study demonstrates the successful development and operation of an oil palm biomassbased renewable energy system integrated with an automated irrigation mechanism using embedded control and real time soil moisture monitoring. The use of an Arduino microcontroller, soil moisture sensors, and automated pumping effectively illustrates how renewable energy harvesting can be combined with precision agriculture to improve water efficiency, reduce manual intervention, and support sustainable farming practices. The experimental results confirm that oil palm biomass pellets can serve as a viable renewable energy source for small scale energy generation while simultaneously powering agricultural automation systems.

Although the current system is implemented as a small scale prototype, it establishes a strong technical foundation for future expansion. To support medium to large scale agricultural operations, several system upgrades are required. These include the use of larger and more efficient turbines and generators capable of handling higher steam flow rates, as well as advanced energy storage systems equipped with intelligent charge controllers and inverters to ensure stable voltage regulation and reliable power distribution. Such improvements are essential for maintaining consistent system performance during peak load conditions and periods of low energy generation. A key aspect of future scalability involves replacing the household pressure cooker with industrial grade biomass boilers. Unlike small domestic equipment, industrial biomass boilers are designed to operate safely at higher temperatures and pressures, allowing continuous steam generation and improved thermal efficiency. This transition significantly enhances electrical output while also addressing critical safety and thermal management requirements. The inclusion of pressure relief systems, temperature and pressure monitoring, fire suppression mechanisms, and appropriate operator training becomes increasingly important as system capacity increases, ensuring safe and dependable long-term operation.

To support larger agricultural fields, the irrigation system must also be expanded into multiple independently controlled zones. Each zone can be equipped with dedicated soil moisture sensors, solenoid valves, and flow control mechanisms to ensure precise and localized water delivery. The use of more advanced microcontrollers or programmable logic controllers enables coordinated control of multiple zones and system components. Furthermore, the integration of wireless communication technologies such as Wi-Fi, LoRa, or GSM allows centralized monitoring and remote control, improving system flexibility and ease of management. From an economic perspective, while large scale implementation requires higher initial investment, the system offers long term financial benefits through economies of scale, reduced dependence on grid electricity or fossil fuels, and improved energy self-sufficiency. Environmentally, the system contributes to the reduction of greenhouse gas emissions by utilizing renewable oil palm biomass and minimizing agricultural waste. At the same time, optimized irrigation reduces water consumption and supports sustainable resource management.

Overall, the proposed system presents a scalable, efficient, and environmentally responsible solution for renewable energy generation and automated irrigation. It is particularly well suited for oil palm producing regions where biomass waste is abundant and readily available. By converting agricultural residues into useful energy and integrating intelligent irrigation technologies, the system supports long-term agricultural productivity, environmental conservation, and sustainable rural development.

Acknowledgement

The research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot Q879).

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Emier Nurman Hazeem, Azuwien Aida Bohari, Khalid Aboubakr Hasan Mousay;* ***Data collection:*** *Emier Nurman Hazeem, Mohd Abdul Talib Mat Yusoh;* ***Analysis and interpretation of results:*** *Azuwien Aida Bohari, Mohd Nizam Mohd Talib, Mohd Norazysyam Azman;* ***Draft manuscript preparation:*** *Emier Nurman Hazeem, Muhammad Rusydi Muhammad Razif, Mohd Norazysyam Azman. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] T. Ahmad and M. Danish, “Prospects of banana waste utilization in wastewater treatment: A review,” J. Environ. Manag., vol. 206, pp. 330–348, 2018.

[2] Admin, “Types of soil - Sandy soil, clay soil, silt soil, and loamy soil,” BYJUS, Jul. 5, 2022. [Online]. Available: https://byjus.com/biology/types-of-soil/

[3] P. Archana and R. Priya, “Design and Implementation of Automatic Plant Watering System,” Int. J. Adv. Eng. Glob. Technol., vol. 4, no. 3, pp. 1567–1570, 2016.

[4] F. Arrieta, F. Teixeira, E. Yanez, E. Lora, and E. Castillo, “Cogeneration potential in the Columbian palm oil industry: Three case studies,” Biomass Bioenergy, vol. 31, no. 7, pp. 503–511, 2007.

[5] M. Balart and G. Ayer, “Biomass Energy in the World, Use of Biomass and Potential Trends,” Energy Sources, vol. 27, no. 10, pp. 931–940, 2005.

[6] T. Brandyk, J. Szuniewicz, K. Skapski, and J. Szatylowicz, “The soil moisture regime study of fen peat soils in the Middle Biebrza Basin as a basis for soil protection,” Z. Kulturtechnik Landentw., vol. 36, no. 2, pp. 78–83, 1995.

[7] A. Gupta et al., “Plant growth–promoting rhizobacteria and their functional role in salinity stress management,” Curr. Microbiol., Jan. 1, 2020. [Online]. Available: https://doi.org/10.1007/s00284-019-01813-6

[8] V. Hallaire, “A 3-dimensional description of cracks networks in clayey soils, using image analysis and a structural model,” Acta Stereol., vol. 8, no. 2, pp. 301–306, 1989.

[9] G. K. Heinrich, European Biomass Statistics 2007: A Statistical Report on the Contribution of Biomass to the Energy System in the EU 27, European Biomass Association, 2007.

[10] A. K. Hossain and P. Davies, “Pyrolysis liquids and gases as alternative fuels in internal combustion engines – A review,” Renew. Sustain. Energy Rev., vol. 21, pp. 165–189, May 2013.

[11] A. Katiyar et al., “Design and Construction of a Shredding Machine for Recycling and Management of Organic Waste,” Int. J. Trend Sci. Res. Dev., vol. 3, pp. 707–712, 2019.

[12] M. Salleh, N. M. N. Nor, N. A. M. Amin, and M. H. Hasan, “Transitioning to a sustainable development framework for bioenergy in Malaysia: Policy perspectives and technology pathways,” Energy, Sustainability and Society, vol. 10, no. 1, pp. 1–17, 2020.

[13] F. A. Norrrahim, N. A. Nurazzi, M. N. F. M. Fauzi, H. M. Akil, and M. R. M. Asri, “Emerging technologies for value-added use of oil palm biomass: A review,” Environmental Science: Advances, vol. 1, no. 3, pp. 223–248, 2022.

[14] M. Hamed, A. A. Rahman, and S. M. Sidik, “Concentrated solar pyrolysis for oil palm biomass: An exploratory review within the Malaysian context,” Renewable and Sustainable Energy Reviews, vol. 188, pp. 113–129, 2023.

[15] M. A. Shukor, N. N. Sulaiman, and A. R. H. M. Kassim, “Feasibility study of palm oil mill waste biomass as Malaysia biofuels feedstocks,” Malaysian Journal of Applied Sciences, vol. 8, no. 1, pp. 25–36, 2023.

[16] M. See, “Palm oil waste can potentially replace Malaysia’s coal power capacity, says minister,” Eco-Business, vol. 15, pp. 14–15, 2025.

[17] N. A. Sulaiman, M. Z. Yusoff, and R. Omar, “Recent advances in oil palm biomass conversion technologies for sustainable energy production,” *Renewable and Sustainable Energy Reviews*, vol. 145, pp. 111–125, 2021.

[18] S. Rahman, A. Ismail, and M. F. Jamaludin, “Performance evaluation of oil palm biomass-based power generation systems in Malaysia,” *Biomass and Bioenergy*, vol. 185, pp. 107–118, 2024.