ASM Sc. J., 21(1), 2026

https://doi.org/10.32802/asmscj.2026.1004

Energy Efficiency Assessment in Hydroponic Systems for Return on Investment (RoI) Enhancement

S.Y. Sim[1]*, S.Z. Islam[1], Z. Ngadiron[1], A.Z.A. Yaakob[1], M.A. Azri[2] and H.L. Kah[3]

[1]*Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia,*
86400 Parit Raja, Batu Pahat, Johor, MALAYSIA
[2]*Gading Kencana Sdn Bhd, Shah Alam, Selangor, Malaysia*
[3]*Electrical and Electronic Engineering Programme Area, Universiti Teknologi Brunei, Bandar Seri*
Begawan BE1410, Brunei

Hydroponic agriculture offers an alternative to conventional farming by enabling higher yields in limited spaces with precise control of nutrients and water. However, its reliance on continuous pumping and monitoring devices results in high energy consumption, increased operational costs, and a slower return on investment (RoI). This paper addresses this issue by developing a solar-powered hydroponic system integrated with floating sensors and an Arduino-based controller to reduce unnecessary pump operation and energy cost. The system was installed at Universiti Tun Hussein Onn Malaysia (UTHM) and monitored for 12 days, with real-time logging of temperature, water level, voltage, and current. Compared with a standard hydroponic system, the proposed setup reduced pump operating cycles and improved energy efficiency. The economic analysis showed that the RoI was −9.56% in the first harvesting session due to the initial setup cost. However, the RoI increased to 80.83%, 171.21%, and 261.65% in the second, third, and fourth harvesting sessions, respectively. The payback period was estimated at approximately two harvesting cycles. These findings indicate that integrating renewable energy with automated water-level control can reduce operating costs and accelerate RoI in hydroponic systems. Future work may include IoT-based monitoring, advanced control strategies, and testing across different crop types and system scales to further improve economic and environmental sustainability.

Keywords: hydroponic; solar-powered; renewable energy; automated monitoring

I. INTRODUCTION

In recent years, growing crops without soil has attracted significant attention through the innovative, sustainable method known as hydroponic cultivation (Vikanksha and Singh, 2023). Among the various hydroponic growing techniques available, higher yields can be achieved because this method allows precise control of nutrients, water, and other environmental factors (Fernandes, Costa & Lemos, 2018). This level of control supports better plant health and faster growth cycles, resulting in increased productivity per unit area.

However, energy consumption in hydroponic systems remains a critical concern, particularly in sustainable agriculture (Banboukian *et al.* 2025). The reliance on electrical components such as grow lights, pumps, and environmental control systems can lead to high energy consumption. As the global population continues to grow, there is an increasing need for efficient, scalable food production systems that are both environmentally responsible and economically viable (Dauchot *et al.*, 2024; Rajendran *et al.*, 2024). At the same time, consumer demand for locally grown, pesticide-free, organic, and high-quality

---

*Corresponding author's e-mail: sysim@uthm.edu.my vegetables at affordable prices further highlights the need for improved energy management in hydroponic systems.

A significant portion of operational costs in hydroponic systems is caused by energy-consuming components, particularly water pumps, air pumps, and climate control systems. Continuous operation of these components, if not properly controlled, can increase electricity bills and reduce the Return on Investment (RoI) for farmers and agribusiness operators (BV, 2024). Therefore, there is a need to develop energy-efficient hydroponic systems that reduce unnecessary energy use while maintaining suitable growing conditions (Choudhury, A and Mahdi, 2023).

Therefore, this study aims to develop and evaluate a solar-powered hydroponic system with sensor-based pump control to reduce energy consumption and improve Return on Investment (RoI). The scope of this study is limited to a small-scale hydroponic system installed at Universiti Tun Hussein Onn Malaysia (UTHM) that uses photovoltaic energy, floating sensors, Arduino-based pump control, and an economic analysis based on several harvesting sessions.

The general methodology of this study involves developing a solar-powered hydroponic system, integrating floating sensors for water-level detection, and implementing an Arduino-based controller to regulate pump operation. The system uses photovoltaic panels as its primary energy source, and the controller activates the pump based on real-time water-level conditions. Data collection included monitoring water usage, ambient temperature, water temperature, voltage, current, and pump operating cycles. The collected data were then analysed in terms of energy consumption and economic performance. Return on Investment was calculated across multiple harvesting sessions to assess cost recovery and long-term profitability of the proposed system.

The findings of this study have important implications for the agricultural sector. By presenting an energy-efficient hydroponic system that balances productivity with energy conservation, this research contributes to ongoing efforts to enhance sustainable food production systems (Mun *et al.*, 2025). In addition, the findings contribute to the literature on precision agriculture and energy-smart farming while providing practical recommendations for real-world applications (Rehman *et al.*, 2024). Farmers, policymakers, and technology innovators can apply these insights to design more cost-effective, scalable, and environmentally sustainable hydroponic farming systems (Cherif *et al.*, 2023).

Furthermore, hydroponic agriculture continues to gain popularity worldwide, particularly in urban farming, rooftop gardens, and controlled-environment agriculture settings. Its ability to produce high-quality crops in a resource-efficient manner makes it an attractive solution for addressing global food security challenges (Dsouza *et al.*, 2023). Recent advancements include the development of energy-saving hydroponic systems powered by solar photovoltaic panels, which reduce dependence on the grid and lower operational costs (Ntinas, Koukounaras and Kotsopoulos, 2015). Additionally, integrating smart cultivation management systems using IoT, artificial intelligence, and cloud-based monitoring has improved system efficiency by enabling real-time monitoring and automated responses to environmental changes (M *et al.*, 2022; Rahman *et al.*, 2024).

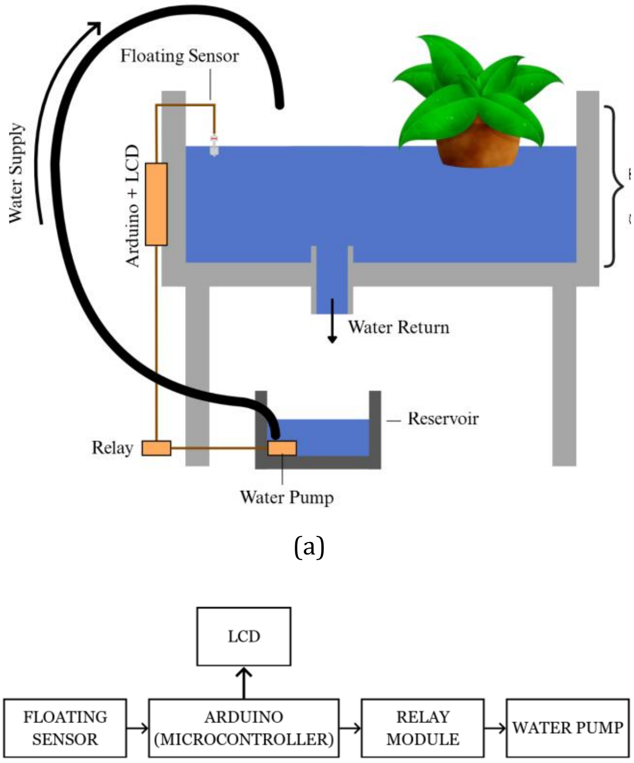
Ultimately, improving energy efficiency in hydroponic systems not only improves financial outcomes for growers but also contributes to environmental sustainability and food system resilience (De Sousa *et al.*, 2024). By combining renewable energy with sensor-based automation, this study demonstrates a practical approach to reducing operational costs and enhancing RoI in hydroponic farming.

II. EXPERIMENTAL SETUPS

This section presents the experimental setups developed for the hydroponic system. It outlines the system's design, component configuration, and overall working principle. The experiment is structured to evaluate the effectiveness of sensor-based automation for water level control, energy usage improvement, and overall system efficiency. The section begins with the experimental design, including the layout of sensors, actuators, and control elements, as illustrated in Figure 1.

A. Design of Experiment

The system will be designed based on the proposed diagram depicted in Figure 1.



(a)

(b)

Figure 1. (a) Prototype design of the project; (b) System block diagram

The floating sensor measures the water level in the grow tray to ensure that the water remains at an optimal level for plant growth. The data collected by the floating sensor is then sent to the Arduino, which acts as the system's microcontroller. Once the Arduino receives the data, it transmits the information to both the LCD and the relay module.

If the data indicates that the floating sensor is in a floating condition, the LCD will display two messages: “Water Level is High” and “Pump is Off.” Conversely, if the sensor is not floating, the LCD will display: “Water Level is Low” and “Pump is On.” The relay module controls the water pump, determining whether it should be turned on or off based on the data received from the Arduino.

The water pump is intended to remain in an "on" state, meaning the floating sensor should not be in a floating condition, as the plant needs to receive nutrients from the fertiliser solution continuously. A water-return drainage system ensures that water in the grow tray continues to circulate, keeping the pump in continuous operation. Figure 2 shows the block diagram of the photovoltaic system.

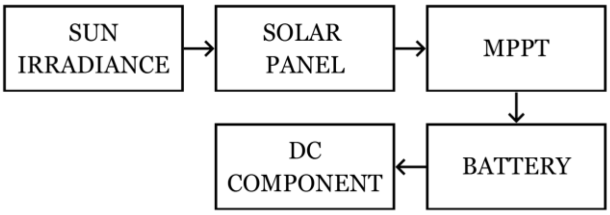


Figure 2. Block diagram of a photovoltaic system

The given block diagram provides a comprehensive illustration of the energy flow within the system, beginning with solar irradiance as the primary energy source. This energy is captured by the solar panel array and directed through an advanced MPPT (Maximum Power Point Tracking) solar charge controller, which dynamically optimises energy harvesting. The system then stores excess energy in a rechargeable battery for later use.

This integrated setup not only efficiently converts solar radiation into direct current (DC) electricity but also ensures energy availability during periods without sunlight, such as nighttime. As a result, a stable and reliable power supply is maintained for various DC components, ensuring continuous operation regardless of solar availability.

B. Experimental Procedure

The hydroponic system will be set up at the UTHM solar site, utilising solar energy to power the system. The Arduino Uno will be used to control and monitor various aspects of the hydroponic setup, including temperature and water levels. Figure 3 above shows that the hydroponic system will include channels for plant growth, a reservoir for the nutrient solution, and a pump to circulate the solution. Solar panels will be installed to supply power to the system. Finally, the Arduino Uno, relay module, temperature sensor, and floating sensor will be integrated into the system.

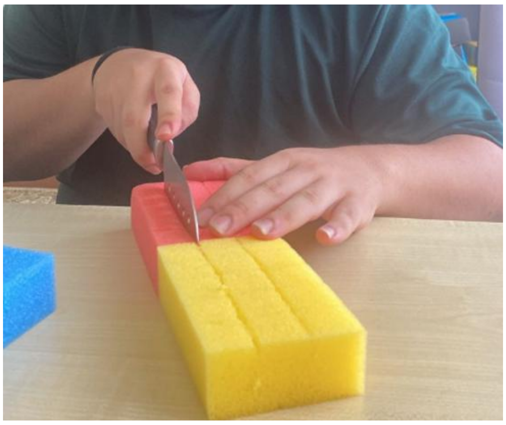
Figure 3. Hydroponic system setup and sensor integration at the project site

C. Plant Planting Process

To plant seeds on a sponge and transfer them to a hydroponic system, first gather the necessary supplies: seeds, a sterile sponge, water, hydroponic nutrient solution, a hydroponic system setup, and a germination container. Figure 4 above shows an example. Cut the sponge into small cubes, about 1–2 inches in size, to hold individual seeds.

The next step is to lightly moisten the sponge cubes with clean water, leaving them slightly damp but not overly wet. To ensure that the seeds remain in contact with moisture, place one or two seeds into each sponge cube and gently press them in.

To keep the sponge moist, place the cubes in a shallow dish or tray that can hold a small amount of water. To maintain a high-humidity environment that promotes germination, cover the tray with a clear lid, plastic wrap, or a humidity dome, as shown in Figure 4(a) and 4(b).



(a)

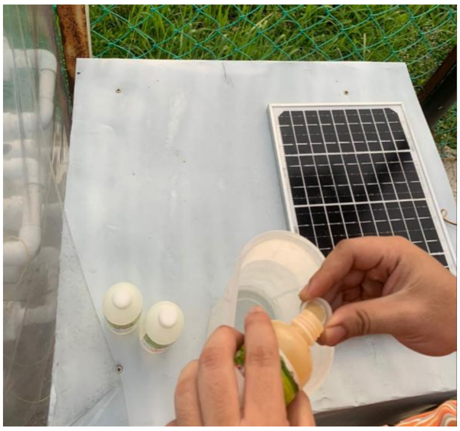
(b)

Figure 4. (a) Sponge preparation for hydroponic use; (b) Seed placement and moistening in sponge cubes

Figure 5 illustrates the types of fertilisers used in this project. The effective use of fertilisers A, B, and C in hydroponics requires a systematic approach. Begin by assembling the necessary materials: the fertilisers, clean water, measuring spoons, and a mixing container.

Next, refer to the instructions on the fertiliser labels to accurately measure and mix the appropriate amounts of fertilisers A, B, and C with water in the designated container. Stir the solution thoroughly until all components are completely dissolved.

Once the nutrient solution is properly prepared, it can be transferred to the hydroponic system's reservoir. Ensure that the reservoir is filled with the carefully mixed solution. For optimal plant health and growth, the system must circulate the solution effectively to ensure uniform nutrient distribution.



(a)

(b)

Figure 5. (a) Fertilising process; (b) Fertiliser types (a, b, and c) used for nutrient solution formulation

Figure 6 shows the measurement method used in this project. Electrical energy calculations are essential because they enable better understanding and more efficient control of power usage. Electrical appliances such as lights, pumps, and sensors require energy, measured in watts or kilowatts, in hydroponic systems. The energy consumption of these devices over time, commonly quantified in watt-hours or kilowatt-hours, can be used to evaluate their impact on electricity costs and overall energy usage.

This information is useful for budgeting, optimising energy efficiency, and ensuring that the hydroponic system operates sustainably without exceeding power limitations. Data collection was conducted over a period of 12 days, with readings recorded every 5 seconds. The data was displayed on an LCD and stored on an SD card.

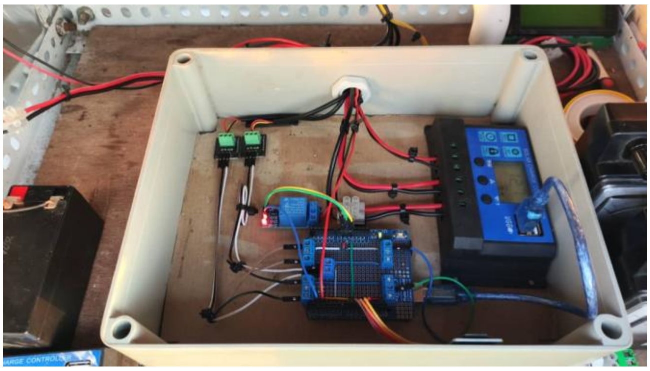


Figure 6. Energy monitoring setup

III. RESULTS AND DISCUSSION

This section presents the results obtained from the experimental hydroponic system and provides a detailed discussion on system performance. The findings focus on key aspects such as voltage and current behaviour of the photovoltaic and battery systems, water usage patterns, pump operation cycles, temperature measurements, and Return on Investment (RoI) analysis. Each section interprets the data collected during the experiment and evaluates how effectively the system achieved its intended objectives, particularly in terms of energy efficiency, automation, and sustainability. Visual representations, such as graphs and figures, are included to support the analysis and highlight key trends and observations.

A. Voltage and Current Measurement for PV

The voltage measurements for the battery and the photovoltaic system are shown in Figure 7. The x-axis represents time, and the y-axis shows voltage in volts. The battery voltage is represented by a continuous line, generally stable with minor fluctuations caused by charging and discharging cycles. Significant dips or spikes may indicate potential issues such as overcharging or deep discharging.

The PV voltage is represented by another line, which varies more significantly and reflects changes in sunlight intensity. Higher PV voltage during peak sunlight hours demonstrates the system's ability to generate sufficient power, while lower values are observed during early morning and late afternoon.

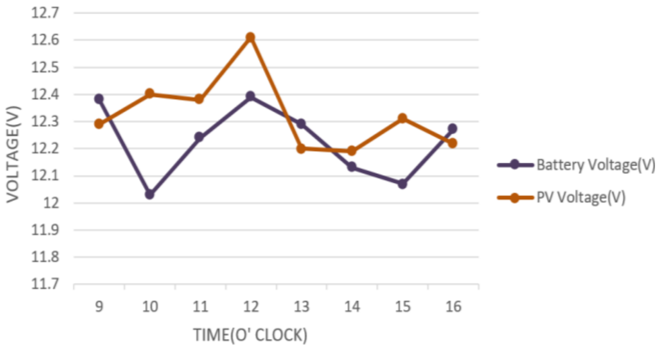


Figure 7. Voltage Variation of Battery and PV System Over Time

The current readings for the battery and PV system are shown in Figure 8. Time is represented on the x-axis, and current in amperes is shown on the y-axis. The continuous line representing the battery current illustrates the charging and discharging cycles that power the hydroponic system. Positive values indicate charging, while negative values indicate discharging. Steady discharge currents during low sunlight periods highlight the battery's role in sustaining the power supply, whereas consistent charging currents during daylight hours reflect the effective operation of the PV system.

Another line represents the PV current, which depends on the intensity of sunlight. Higher values occur during peak sunlight hours, while lower values are observed during times of reduced sunlight. This data helps evaluate the performance and efficiency of the solar panels in converting sunlight into electrical energy.

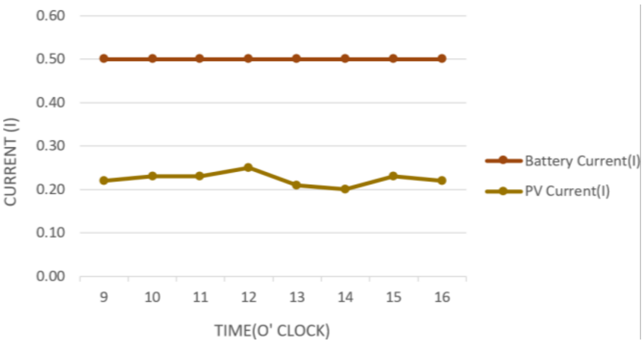


Figure 8. Current Variation of Battery and PV System Over Time

B. Water Consumption per Day

The hydroponic system's daily water use over several days is shown in Figure 9(a). The y-axis indicates the amount of water consumed (in litres), while the x-axis represents the days on which measurements were taken. Each bar on the graph represents the total volume of water used by the hydroponic system on a specific day.

This graph illustrates how water consumption varies across different environmental factors, plant growth stages, and potential system adjustments. For instance, higher water usage on certain days may result from increased evaporation during hotter weather or heightened plant water requirements during growth spurts. In contrast, lower consumption on other days could be due to cooler temperatures or reduced plant activity.

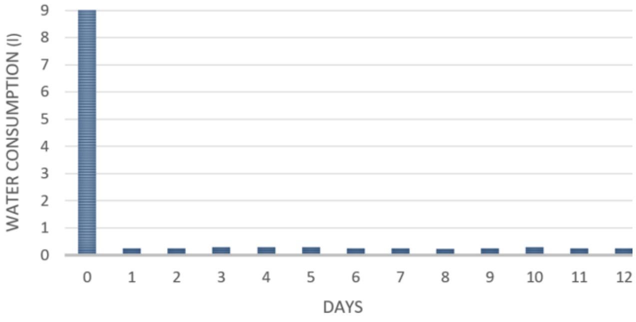
Understanding water demand patterns in the hydroponic system requires interpreting the data shown in Figure 9(a). By analysing this graph, system managers can plan water resource management more effectively, ensuring sufficient supply while minimising waste. This information can also be used to enhance system efficiency. For example, by adjusting watering schedules and volumes to meet plant and environmental needs more precisely.

The relationship between water usage and water height in the hydroponic system is illustrated in Figure 9(b). In this graph, the x-axis represents the system's water height, while the y-axis displays the corresponding water consumption in litres. Each point on the graph corresponds to a recorded measurement of water use at a specific water level.

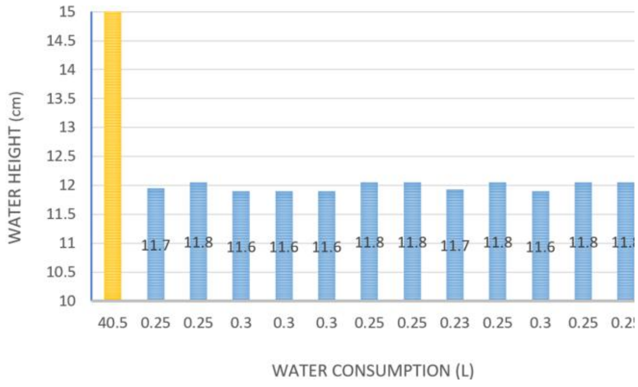
Figure 9(b) shows how fluctuations in water height correlate with water usage. Higher water levels are often associated with lower water consumption, possibly due to reduced plant uptake. On the other hand, lower water levels may indicate increased water usage, potentially due to greater evaporation on sunny days.

Understanding the relationship shown in Figure 9(b) is essential for maintaining optimal water levels in the hydroponic system. By observing this relationship, operators can ensure that water height remains within a suitable range, reducing excess usage and potential loss while maintaining an adequate supply for plant needs. This balance is critical for both sustainable water resource management and efficient system performance.

These detailed analyses of Figures 9(a) and 9(b) provide a comprehensive understanding of water usage patterns in the hydroponic system, supporting improved resource planning and system strategies.



(a)



(b)

Figure 9. (a) Daily water consumption of the hydroponic system; (b) Relationship between water height and water consumption

C. *Ambient and Water Temperature Measurement*

A comprehensive view of temperature variations is presented in Figure 10, based on merged data collected on June 7, 12, and 17, 2024. The y-axis displays temperature in degrees Celsius, and the x-axis shows time of day over 24 hours. Multiple lines are shown on the graph, each representing the water and ambient temperatures for the corresponding day.

The graph reveals clear patterns in ambient temperature changes throughout the day, with a noticeable rise in the morning, a peak in the afternoon, and a gradual decrease in the evening. Although water temperature follows a similar trend, the fluctuations are less pronounced because water's higher specific heat capacity causes it to heat up and cool down more slowly.

When comparing the three dates, June 12 shows a slightly higher peak ambient temperature than June 7 and 17, indicating a hotter day. The ambient temperature also peaks earlier than the water temperature, although the overall trend remains consistent. Because water responds to temperature changes more slowly than air, it serves as a more stable medium for hydroponic systems.

The combined data shown in Figure 10 is essential for optimising the system to prevent plants from being exposed to excessive heat. By understanding these temperature patterns, system controls can be adjusted accordingly. For example, by modifying water pump cycles or implementing shading and cooling techniques during periods of high temperature. This detailed analysis supports maintaining optimal growing conditions, thereby enhancing the efficiency and reliability of the hydroponic setup.

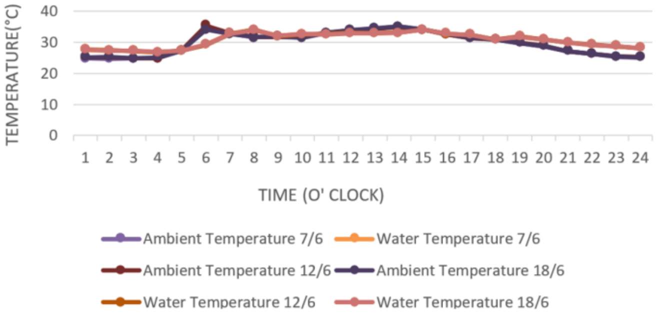


Figure 10. Comparison of ambient and water temperature throughout the day on selected dates

D. *Water Pump Cycle*

The water pump operating times for standard and optimised hydroponic systems are compared in Figure 11. In the standard setup, the water pump operates consistently and regularly every hour of the day, regardless of the actual water level required. This results in a pattern of continuous but inefficient energy use. The pump runs for a fixed duration each hour, represented by uniform bars in the graph. This consistent operation highlights the standard system's inability to adapt to real-time changes in plant needs and water levels.

In contrast, the optimised system demonstrates a more sporadic and targeted approach to water pump activation. The pump operates only when necessary, based on sensor inputs that monitor actual water levels and plant requirements. As a result, pumping durations are shorter and less frequent, as evidenced by fewer, shorter bars appearing at irregular times throughout the day. This irregular pattern reflects more efficient energy usage, as the pump is activated only when the water level drops below a specific threshold, thereby conserving energy and reducing unnecessary operation.

The visual comparison in Figure 11 clearly illustrates the advantages of the optimised system. Its responsiveness leads to significant energy savings and may extend the water pump's lifespan by reducing operational stress. This diagram effectively captures the research's primary objective: enhancing the energy efficiency of hydroponic systems through intelligent sensors and control mechanisms. The data suggests that an improved system ensures more precise water delivery to plants when needed, improving both energy conservation and plant growth and productivity.

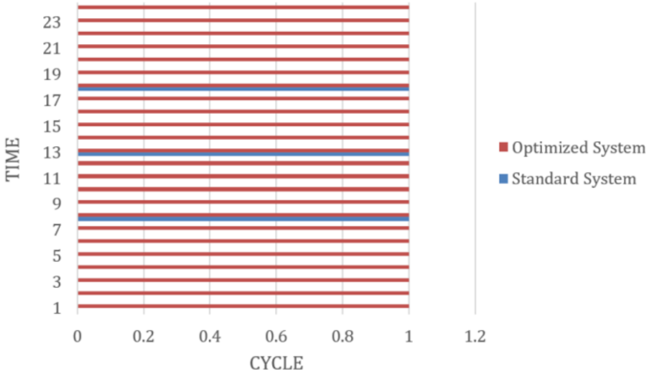


Figure 11. Comparison of water pump operating cycles in standard and optimised hydroponic systems

E. *Return On Investment (R.O.I) Calculation*

The Return on Investment (RoI) for the hydroponic system was calculated based on the total amount spent and the total revenue gained from growing Pak Choy. The total expenditure for the system was $348.40, while the revenue from selling the Pak Choy was $315, as shown in Table 1. To calculate the RoI, the difference between the amount gained and the amount spent was divided by the total amount spent, and the result was then multiplied by 100 to convert it into a percentage, as shown in (1).

Table 1. Financial data of the hydroponic system for Roi analysis

Item	Price ($)
Amount Spent	348.40
Pak Choy Price (per unit)	4.50
Number of Holes (Plants)	70
Amount Gained	315

$$ROI = \left(\frac{315 - 348.4}{348.4}\right) \times 100 \qquad (1)$$

This calculation resulted in an RoI of −9.56% for the first harvesting session. This means the investment in the hydroponic system resulted in a 9.56% loss relative to the initial amount spent.

In addition, the profit trends across four harvesting sessions (RoI) are illustrated in Figure 12. The first session shows a -9.56% loss. However, in the second session, a profit of 80.83% is recorded, indicating a noticeable improvement and suggesting that the implemented changes were effective. The upward trend continues with a 171.21% profit in the third session, followed by a further increase to 261.65% in the fourth session. This consistent upward trend suggests that the applied strategies are successful and that the system's financial performance is improving over time.

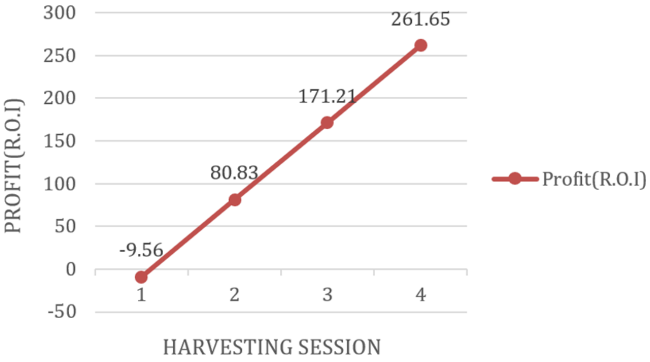


Figure 12. R.O.I trend over four harvesting sessions

F. *Payback Period Calculation*

The formula for calculating the payback period of the hydroponic system is given in (2). This equation relates the total expenditure of the system to the total revenue gained from crop sales:

$$Payback = \left(\frac{Amount\ Spent}{Amount\ Gained}\right) \qquad (2)$$

The payback period for the hydroponic system was calculated by substituting the total amount spent of $348.40 and the amount gained of $315 from the first harvesting session into (2), the payback period is obtained as 1.1 harvesting sessions. When rounded up, this means it will take 2 complete harvesting sessions of growing and selling Pak Choy to recover the initial investment.

IV. CONCLUSION

As demonstrated in this paper, improving energy efficiency in hydroponic systems is important for enhancing Return on Investment (RoI) and overall system performance. The solar-powered hydroponic system developed at Universiti Tun Hussein Onn Malaysia (UTHM) successfully integrated ambient and water temperature sensors with floating sensors to control pump operation, thereby reducing unnecessary energy consumption. The results showed that the first harvesting session recorded a negative RoI of −9.56% due to the initial investment cost. However, the RoI improved significantly in the following sessions, reaching 80.83%, 171.21%, and 261.65% in the second, third, and fourth harvesting sessions, respectively. The payback period was achieved in approximately two harvesting cycles, confirming the economic feasibility of the proposed system.

The key scientific contribution of this work lies in demonstrating how sensor-based automation can be practically applied to hydroponic farming to reduce energy demand and improve financial returns. Unlike many studies that focus mainly on crop growth or energy modelling, this paper provides experimental evidence on the relationship between automated pump control, energy efficiency, and RoI performance. These findings can guide the future development of sustainable hydroponic systems that balance productivity, cost savings, and environmental responsibility.

V. ACKNOWLEDGEMENT

This work was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Multidisciplinary Research Grant (MDR) (Q708) and Postgraduate Research Grant (GPPS) (J192).

VI. REFERENCES

Banboukian, A *et al.* 2025, 'The challenges of controlled environment hydroponic farming: A life cycle assessment of lettuce', The International Journal of Life Cycle Assessment, vol. 30. doi: 10.1007/s11367-025-02463-6.

BV, T 2024, 'Cost-benefit analysis of hydroponic farming: Growing lettuce under nutrient film technique in India', Educational Administration: Theory and Practice, pp. 1623–1627. doi: 10.53555/kuey.v30i5.3140.

Cherif, D, Ayed, R, Skouri, S, Bouadila, M, Lazaar, M & Guizani, A 2023, 'Enhancing crop yield in hydroponic greenhouses: Integrating latent heat storage and forced ventilation systems for improved thermal stratification', Thermal Science and Engineering Progress, vol. 45, article 102163. doi: 10.1016/j.tsep.2023.102163.

Choudhury, T, A, R & Mahdi, HF 2023, 'Optimized crop detection using IoT and deep neural networks', in 2023 5th International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA), IEEE, Istanbul, pp. 1–6. doi: 10.1109/HORA58378.2023.10156699.

Dauchot, G, Aubry, C, Crème, A, Dorr, E & Gabrielle, B 2024, 'Energy consumption as the main challenge faced by indoor farming to shorten supply chains', Cleaner and Circular Bioeconomy, vol. 9, article 100127. doi: 10.1016/j.clcb.2024.100127.

De Sousa, R, Bragança, L, Da Silva, MV & Oliveira, RS 2024, 'Challenges and solutions for sustainable food systems: The potential of home hydroponics', Sustainability, vol. 16, no. 2, article 817. doi: 10.3390/su16020817.

Dsouza, A, Newman, L, Graham, T & Fraser, ED 2023, 'Exploring the landscape of controlled environment agriculture research: A systematic scoping review of trends and topics', Agricultural Systems, vol. 209, article 103673. doi: 10.1016/j.agsy.2023.103673.

Fernandes, MB, Costa, BA & Lemos, JM 2018, 'Hydroponic greenhouse crop optimization', in 2018 13th APCA International Conference on Control and Soft Computing (CONTROLO), IEEE, Ponta Delgada, pp. 270–275. doi: 10.1109/CONTROLO.2018.8514264.

Kumar, V, Arun & Singh, J 2023, 'Trends in hydroponics practice/technology in horticultural crops: A review', International Journal of Plant & Soil Science, vol. 35, no. 2, pp. 57–65. doi: 10.9734/ijpss/2023/v35i22759.

M, SP *et al.* 2022, 'Intelligently optimized system for hydroponic cultivation', in 2022 International Conference on Communication, Computing and Internet of Things (IC3IoT), IEEE, Chennai, pp. 1–5. doi: 10.1109/IC3IOT53935.2022.9767724.

Mun, H, Lagua, EB, Hong, S, Ryu, S, Sharifuzzaman, M, Hasan, MK, Kim, Y & Yang, C 2025, 'Energy-efficient technologies and strategies for feasible and sustainable plant factory systems', Sustainability, vol. 17, no. 7, article 3259. doi: 10.3390/su17073259.

Ntinas, GK, Koukounaras, A & Kotsopoulos, T 2015, 'Effect of energy saving solar sleeves on characteristics of hydroponic tomatoes grown in a greenhouse', Scientia Horticulturae, vol. 194, pp. 126–133. doi: 10.1016/j.scienta.2015.08.013.

Rahman, MA, Chakraborty, NR, Sufiun, A, Banshal, SK & Tajnin, FR 2024, 'An AIoT-based hydroponic system for crop recommendation and nutrient parameter monitorization', Smart Agricultural Technology, vol. 8, article 100472. doi: 10.1016/j.atech.2024.100472.

Rajendran, S, Domalachenpa, T, Arora, H, Li, P, Sharma, A & Rajauria, G 2024, 'Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with emphasis on potato mini-tuber cultivation', Heliyon, vol. 10, no. 5, article e26823. doi: 10.1016/j.heliyon.2024.e26823.

Rehman, AU, Alamoudi, Y, Khalid, HM, Morchid, A, Muyeen, S & Abdelaziz, AY 2024, 'Smart agriculture technology: An integrated framework of renewable energy resources, IoT-based energy management, and precision robotics', Cleaner Energy Systems, vol. 9, article 100132. doi: 10.1016/j.cles.2024.100132.