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Integration of Solar Panels and Arduino for Aquaponic System Automation and Solar Energy Efficiency

Lailatul Husna Lubis[1*], **Mesyadi**[1], **Mulkan Iskandar Nasution**[1]
[1] *Physics department, Faculty of Science and Technology, State Islamic University of North Sumatera*

Corresponding Authors E-mail: lailatulhusnalubis@uinsu.ac.id

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Abstract

Aquaponics is a system that combines fish and plant farming in one mutually beneficial ecosystem. However, the consumption of electrical energy, such as driving water pumps in aquaponic systems, is crucial because it requires considerable financing. Solar panels are one of the alternatives in reducing the use of electrical energy. Solar energy is environmentally friendly and does not produce pollution like conventional energy. Thus, automation and using solar energy as renewable energy can be a solution to improving the efficiency of aquaponic systems. This research aims to analyze the Arduino-based automation system and the use of 200 Wp solar panels in aquaponics involving catfish and water spinach cultivation. The system uses solar panels as the primary energy source stored in VRLA batteries, regulated through a Solar Charge Controller, and converted into AC electricity to operate the water pump and automatic monitoring system. Arduino Uno controls the automation and monitoring with pH, TDS, temperature, humidity, and ultrasonic sensors to monitor environmental conditions. Tests show that the solar panel produces an average voltage of 40.83 V and a current of 3.28 A, with an efficiency of 40.65% and a power that can be generated in a day of 1200 Watts. The operational cost of the solar panel system was calculated using the Levelized Cost of Energy (LCOE), showing that it is more efficient than PLN electricity at Rp 688.15/kWh vs. Rp 1,444.70/kWh or Rp 31,397.3 vs. Rp 65,947.35 for one year of aquaponic system use. Monitoring for 10 days showed optimal growth of water spinach and catfish plants with consistent pH, temperature, humidity, and pump and servo operation. The results indicate that an aquaponics system powered by renewable energy and Arduino-based automation effectively meets energy needs at a lower cost and improves the efficiency and reliability of aquaponics operations.

Introduction

Aquaponic farming is an eco-friendly agricultural method integrating aquaculture (fish farming) with hydroponics (growing plants without soil) to create a symbiotic environment. In this system, fish waste serves as a nutrient source for the plants, while the plants naturally purify the water, which is then circulated back to the fish tanks [1], [2]. The efficiency and sustainability of aquaponics make it a promising option for contemporary farming, particularly in regions where water is scarce [3].

Aquaponic systems have been proven as a sustainable method of farming. However, commercialization and long-term management challenges, especially energy efficiency and automation, remain significant obstacles to their large-scale implementation. The sustainability and scalability of aquaponic systems require optimizing energy resources and automation to lower operational costs and increase production efficiency [4]. Conventional aquaponic systems that rely on the power grid face significant operational challenges, especially in terms of high energy costs, as an analysis conducted by Yudi showed an energy consumption of 579.6 Wh per day [5], while a study by Andansari et al. recorded a total daily energy use for aquaponic systems reaching 4,608 Wh [6]. The use of renewable energy, such as solar panels that convert solar energy into electrical energy, is an attractive alternative and has the potential to reduce dependence on conventional electricity and provide significant environmental benefits [7].

Beyond energy efficiency, the effectiveness of aquaponic systems hinges on the capacity to regulate and track key environmental factors like temperature, humidity, water and soil pH, total dissolved solids (TDS), and plant growth, crucial elements for system success. Automation systems based on Arduino technology provide a cost-effective and efficient way to oversee aquaponic operations in real-time. By incorporating sensors and actuators, these systems can enhance conditions for fish and plants, boost productivity, and minimize running costs.

To support energy efficiency in Arduino-based aquaponics systems, selecting renewable energy devices is also an important aspect that must be considered, including the type of solar panel used. Monocrystalline solar panels were chosen for this system because they have a higher energy conversion efficiency than polycrystalline panels. Monocrystallines are known for their superior performance, especially in lower lighting conditions, which is essential in the context of regions with variability in sunlight intensity. They have up to 20% conversion efficiencies, so two 100 Wp panels can produce more energy than polycrystalline alternatives with lower efficiencies. In addition, monocrystalline also has a longer lifetime, making it ideal for systems that require a consistent energy supply to support automation and pumps in aquaponics systems. In addition, these solar panels were chosen over smaller or larger alternatives because of the balance between cost, power generated, and installation space availability. The selection of monocrystalline solar panels is also supported by using an MPPT Solar Charge Controller (SCC), which can optimally utilize the high efficiency of monocrystalline by adjusting the input voltage to suit environmental conditions. The system is optimized to collect and store energy at the maximum level, even when the weather is unfavorable, so the power supply for pumps and automation systems remains stable. The selection of 100 Ah VRLA batteries ensures that the energy generated by the solar panels can be stored efficiently and used sustainably at night or when sunlight is lacking. The pure sine wave inverter used in this system is also selected based on its high efficiency, so the energy generated is not wasted when converted from DC to AC.

Previous research has explored various aspects of aquaponic systems, including the use of sensors to monitor environmental parameters and the application of microcontrollers for automation, which can increase electricity demand in system operations [8], [9], [10], [11]. Nasution et al., in their research entitled Implementation of IoT-Based Microcontroller to

Optimize the Performance of Aquaponic Systems, created an aquaponic system device control tool via the internet with a remote control system that can control the operation of recirculation pumps and fish feed devices and provide real-time information on pond water conditions (temperature and pH), as well as pump operation and automatic feeding scheduled three times a day [12]. However, integrating renewable energy, particularly solar panels, into aquaponic systems is still under-explored. According to a study by Purnomo et al., using solar panels in aquaponics can reduce dependence on the conventional power grid. However, further research is needed to understand energy efficiency on a larger operational scale [13]. In addition, Arduino-based automation has been shown to increase efficiency and reduce manual labor in aquaponic systems. Still, studies examining the integration between solar panels and Arduino in this context are limited.

Several studies have explored the use of renewable energy, particularly solar panels, as a solution to reduce dependence on conventional energy sources [14], [15], [16], [17], [18]. Asy'ari et al., in their research that utilizes solar panels as a source of electrical energy for residential homes, concluded that 200 Wp solar cells could provide enough electricity to power the lighting system [19]. This shows the great potential of solar energy in meeting the energy needs of aquaponic systems.

The potential of solar panels as a renewable energy solution is not only apparent in aquaponic systems, but also the context of operational costs. Through the LCOE (Levelized Cost of Energy) approach [20], Agyekum et al. conducted a case study to assess two possible energy sources: nuclear energy and solar energy, in the Republic of Ghana using the LCOE matrix to evaluate the average cost required to produce one unit of electricity in energy over its operational life, the results showed that solar power plants require lower costs than nuclear power plants [21].

Building on the previous discussion, integrating solar panels with microcontrollers such as Arduino in this context has not been explored in depth. This research evaluates the integration of solar panels with Arduino-based automation in aquaponic systems. This research emphasizes the efficiency of solar panel-powered electrical systems without directly assessing the energy savings attributed to automation. This research aimed to assess the effectiveness of utilizing solar panels as the primary energy source for aquaponic systems, design an Arduino-based automation control system to enhance catfish farming operations and implement a monitoring system for water spinach growth to boost overall productivity. The research involved hands-on experiments that integrated solar panels, Arduino modules, and various sensors for real-time monitoring and management of the aquaponic environment. In addition, an analysis of the operational cost of solar panels compared to the use of electricity from PLN will be conducted to assess the potential for long-term savings. The collected data is quantitatively analyzed to evaluate the energy efficiency, system performance, and its effect on plant growth and operational cost efficiency of the aquaponics system. Limitations of this study include the lack of comparison with manual systems or systems without automation, and the analysis was mainly limited to the electrical and monitoring components.

Experimental Method

This study employed an experimental approach to assess the efficiency and reliability of an aquaponic system powered by renewable energy and equipped with automation and monitoring features. The aquaponic setup involved the cultivation of catfish and water spinach, using solar panels as the primary energy source. Arduino technology was implemented to control automation, while various sensors were used to track and monitor environmental conditions. This research conducted tests only on the Arduino-based system supported by solar panels without direct comparison to manual systems or conventional systems without automation. The main focus was on evaluating the energy efficiency of the electrical system and the effectiveness of sensor-based automation. This study utilizes two monocrystalline solar panels, each with a capacity of 100 Wp, connected to a 60A MPPT Solar Charge Controller (SCC) and a 12 Volt 100 Ah VRLA battery for energy storage. The stored energy is then transformed into AC electricity via a pure sine wave inverter, which powers the automation and monitoring system. Additionally, the electricity is used to operate two water pumps, responsible for circulating water in the fish pond and irrigating the plants.

The system utilizes two Arduino Uno boards as the primary microcontrollers to manage the aquaponic pond and plant operations. Each Arduino is connected to a relay that functions as a switch for controlling water pumps, and an RTC DS3231 module is used to schedule pump operation. For pond monitoring and automation, a submersible pump circulates the water. At the same time, the Arduino integrates an HC-SR04 ultrasonic sensor to track water levels, a servo motor for managing fish feeding, and various sensors such as a DS18B20 for temperature, a pH sensor, and a TDS sensor to monitor water quality. On the plant side, an external pump typically used in households handles irrigation, and the Arduino is equipped with two HC-SR04 ultrasonic sensors to monitor plant growth in the first and second fields. Additionally, it includes DHT11 temperature and humidity sensors, two soil moisture sensors, and two pH sensors to assess soil quality and environmental conditions across both growing areas. The sensor data is automatically saved to an SD card module and simultaneously displayed on an I2C LCD for real-time monitoring, with the information being recorded for further analysis.

Figure 1. Implementation of microcontroller technology and renewable energy in aquaponics system

Arduino was chosen as the main microcontroller platform due to its broad compatibility with the various sensors used in these systems and the energy efficiency it offers. In addition, Arduino's wide use in the aquaponics community and the availability of open-source code libraries make it easy to develop and integrate automation. The various sensors used in this system, including the pH sensor, soil moisture sensor, temperature sensor, TDS sensor, and ultrasonic sensor, were calibrated before being integrated into the system. Calibration is carried out using calibrated test equipment that meets SNI standards as a comparison for the measurement results of the sensors used. The steps start with soil and water pH sensors, where standard buffer solutions (pH 4, 7, 10) match the sensor results with the SNI reference tool, ensuring sensor cleaning is carried out at each solution change. The soil moisture sensor is calibrated by comparing the sensor results with those of reference soil whose moisture has been measured using the SNI tool. Air temperature and humidity sensors require placement in a room with stable conditions measured by a reference tool, comparing results and correcting differences manually or automatically. For water temperature sensors, calibration is done by dipping the sensor into a water container with a known temperature through the SNI tool. TDS sensor calibration involves a standard solution with a specific concentration (e.g. 342 ppm) to match the sensor measurement results with a reference tool. Finally, the ultrasonic sensor is calibrated by measuring the distance of the object at various positions (e.g. 10 cm, 50 cm, 100 cm), comparing it with the SNI distance measuring instrument, and the difference in the values of all sensors with the SNI measuring instrument is adjusted for error via software. All steps are performed under stable environmental conditions to ensure accuracy and consistency. Optimization was carried out to ensure each sensor could operate under varying aquaponic environmental conditions. The selection of these sensors was based on their reliability in aqueous environments and their ability to monitor parameters over long periods without degradation in accuracy continuously.

In the automation and monitoring setup for the plant section, the Arduino's analog input pins A0 and A1 are connected to the A0 pins of the soil moisture sensors for the first and second planting fields. The Arduino automatically converts the analog signal from the soil moisture sensor into digital data using the built-in ADC (Analog-to-Digital Converter). The analog value coming into the analog pin is converted into a digital value with a 10-bit resolution, resulting in a range of values between 0 and 1023. This digital value is then interpreted as the percentage of soil moisture based on the sensor calibration. Similarly, analog pins A2 and A3 are wired to the output pins of the pH sensors for monitoring soil conditions in both fields. The Arduino’s analog input pins A4 and A5 are connected to the SDA and SCL pins of the RTC and LCD modules. For the first ultrasonic sensor, digital input pins 2 and 3 are linked to the TRIGGER and ECHO pins, while pins 4 and 5 perform the same function for the second ultrasonic sensor. Digital pin 6 is connected to the DATA pin of the temperature sensor, and pin 7 is assigned to the relay’s input pin. The SD Card module's CS, SCK, MOSI, and MISO pins are wired to digital I/O pins 10, 13, 11, and 12, respectively. The VCC pins of all sensors and modules are connected to the Arduino's 5V power rail, and all GND pins are tied to the ground rail. The Arduino Uno is programmed through a USB connection to a PC, as illustrated in Figure 2. The plant monitoring system application is depicted in Figure 3, and the program code for system management can be seen in the Supplementary Information (Figure S1).

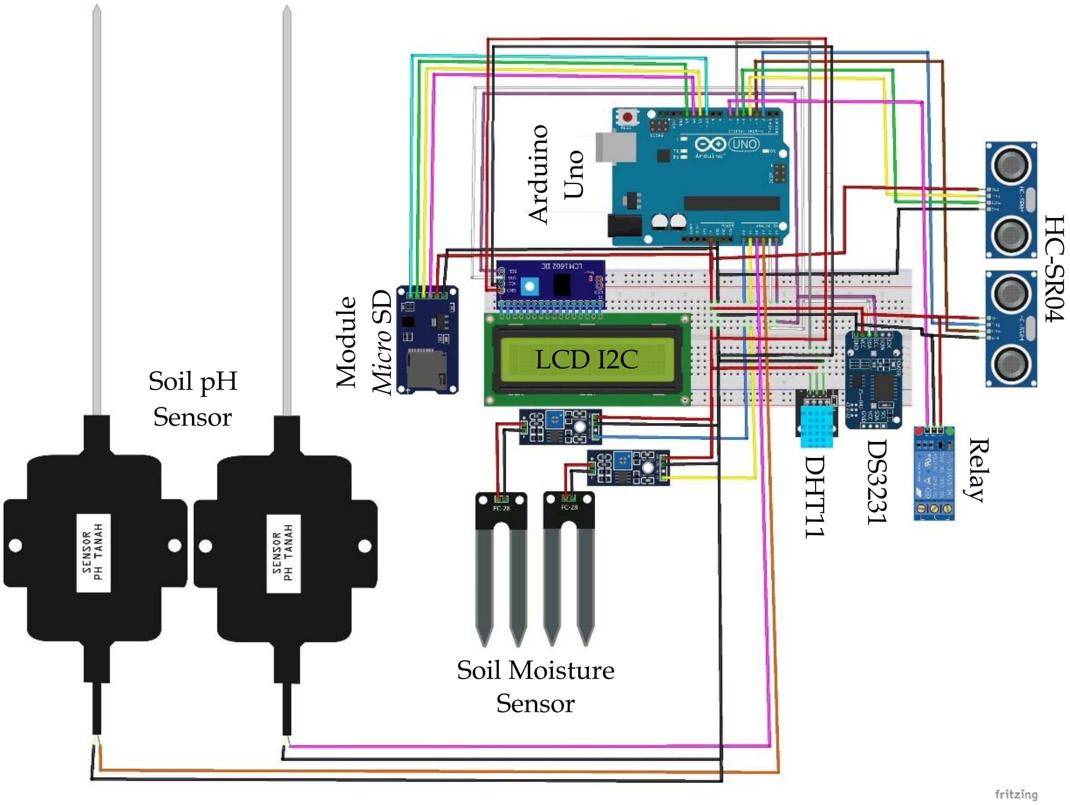

Figure 2. Connecting and integrating sensors with an Arduino microcontroller for plant management.

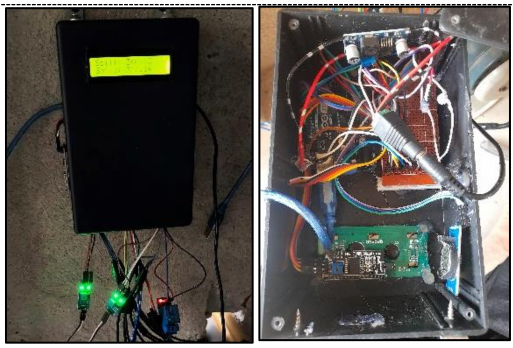

Figure 3. Final product microcontroller system with integrated sensors for plant management

In contrast, the automation and monitoring of the fish pond section utilize different sensors. As illustrated in Figure 5, the Arduino's A0 analog pin is connected to the pH sensor's Po pin, while the A1 analog pin is linked to the TDS sensor. Digital input pins 2 and 3 are wired to the TRIGGER and ECHO pins of the ultrasonic sensor. The temperature sensor connects to digital pin 8, and the servo's data pin is attached to digital input pin 9. The fish pond monitoring system application is depicted in Figure 6, with the program code for system management can be seen in the Supplementary Information (Figure S2).

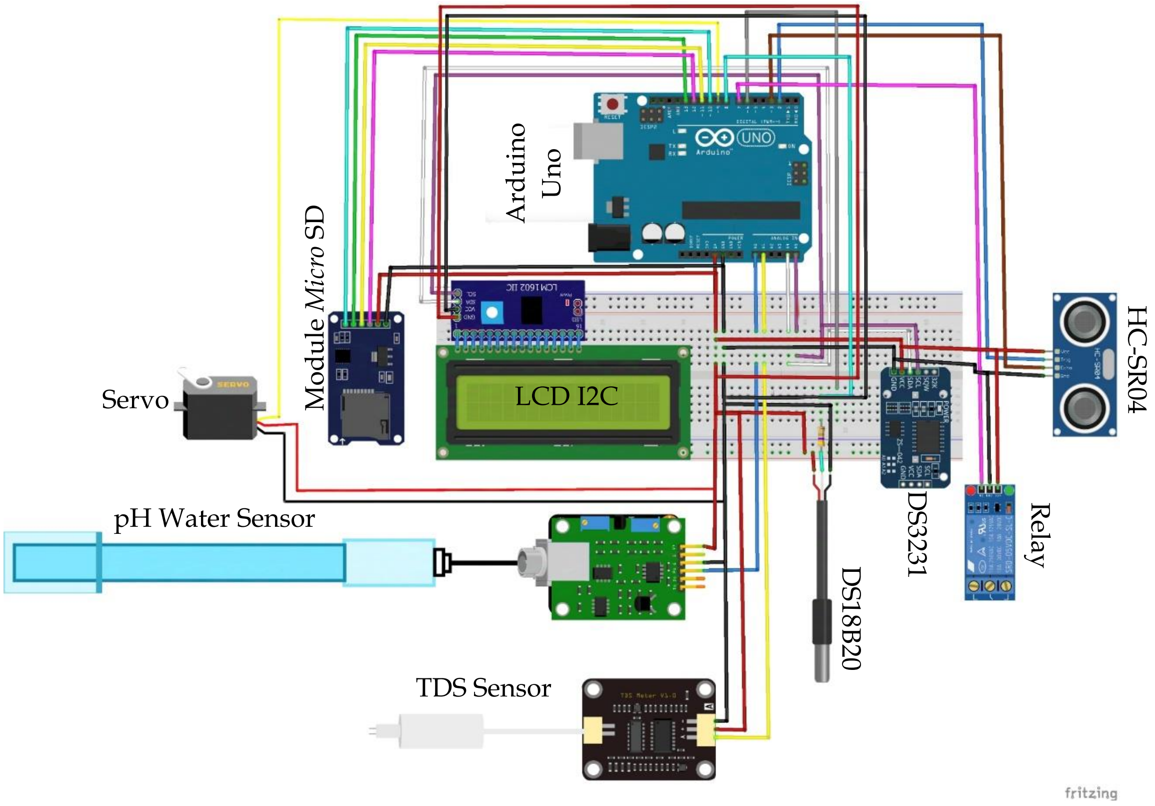

Figure 5. Connecting and integrating sensors with an Arduino microcontroller for fish pond management

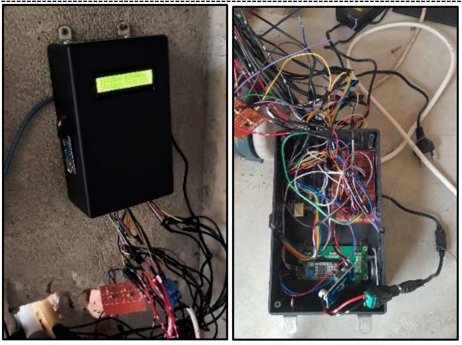

Figure 6. Final product microcontroller system with integrated sensors for fish pond management

The efficiency of the solar panel is analyzed by gathering test data on the voltage and current passing through the panel, which is monitored via the Solar Charge Controller (SCC) display. Data collection occurred over one day, from 07:00 to 18:00 WIB, with measurements taken every hour, using a digital multimeter to measure voltage and current. The SCC monitor screen used in this study can also show the voltage and current values. Additionally, light intensity was measured using a lux meter with the solar panel positioned at a 60-degree angle on the roof. The measurement results were then converted into light intensity values (1 lux =

0.0079 W/m²) [22]. This data allows for the calculation of solar panel efficiency using the formula provided by [23]:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \tag{1}$$

$$\eta = \frac{V_{avg} \times I_{avg} \times FF}{Ir \times A} \times 100\% \tag{2}$$

Description:

η = Solar cell efficiency (%)
V = Average voltage (Volt)
I = Average current (Ampere)
FF = *Fill Factor* (%)
Ir = Solar intensity (W/m²)
A = Solar panel surface area (m²)

Fill Factors (FF) are a key indicator of solar cell performance. The Fill Factor is a dimensionless value representing the ratio of the maximum power output from a solar cell to the product of the open-circuit voltage (Voc) and short-circuit current (Isc). When the resistance is extremely high or approaches infinity (open circuit), the current drops to zero, while the voltage reaches its peak. This voltage is referred to as the open-circuit voltage (Voc). On the other hand, when the resistance is nearly zero, the current reaches its maximum while the voltage drops. This condition is the short-circuit current (Isc) [24].

The operational expenses of solar power plants are assessed and compared using the Levelized Cost of Energy (LCOE) approach. This method calculates the cost per unit of energy produced throughout the system's economic lifespan. The calculation follows the formula provided by [25]:

$$LCOE = \frac{CapEx + \sum OpEx}{\sum E_{generated/year}} \tag{3}$$

CapEx represents the upfront investment cost, while OpEx refers to the ongoing operational and maintenance expenses. E denotes the total energy generated by the solar panel system. In the aquaponics automation and monitoring system for plants and ponds, the sensors connected to the Arduino Uno were pre-calibrated by comparing the system's LCD readings with SNI standard measuring instruments. This ensures that the aquaponics monitoring system provides highly accurate measurements. The system's program includes scheduling for the pump and servo, with monitoring data being recorded on the SD card module every 30 minutes, resulting in 48 data points per day. After 10 days of monitoring, the collected data is compiled for analysis.

Result and Discussion

Voltage, current, and light intensity tests on the solar panel, as shown in Table 1, obtained an average voltage of 40.83 V, current of 3.28 A, and light intensity of 249.12 W/m². Of all the data obtained, some shows that the voltage value is still low when the lux value is high. After we studied, some of the possibilities that cause this include high panel temperature; if the temperature is too hot, it can reduce energy conversion efficiency. Another cause is inappropriate light quality because solar panels require light in a certain spectrum; if the light source contains a less-than-optimal spectrum, the energy conversion efficiency will also decrease. The average power, calculated by multiplying the voltage and current, was 119.14 Watts under cloudy conditions, close to its nominal capacity. However, higher temperatures tend to decrease the output voltage by 0.28 V/°C. Although the effect of temperature on voltage is in line with theoretical predictions, the effect is smaller than expected. In the context of aquaponics, this means that the system can still function well under higher temperature conditions, which often occur in the tropics. When compared to the study by Asy'ari et al., our system produced more optimal power in less favorable weather conditions.

Based on the linear regression performed between temperature and voltage in Figure 8, the correlation coefficient of $R = 0.0215$ indicates that although there is a negative relationship between temperature and panel voltage, the effect is insignificant in lowering the overall power efficiency. This is consistent with the theory that higher temperatures can reduce the performance of solar panels [26]. However, in this case, the effect is still within acceptable tolerance limits for aquaponic applications. A similar study by Dahliya et al. found a correlation level of $R = 0.0281$ in polycrystalline solar panels, slightly higher than our findings in monocrystalline panels [27]. This suggests that the type of solar panel and the quality of the environment may affect the sensitivity to temperature changes. Several factors can affect the efficiency and performance of solar panels, including short test duration, manufacturer's product quality (technical specifications), panel surface and ambient temperature, wind speed, dust accumulation on the panels, and installation settings (such as shading, panel orientation, type of charge controller, and cables used). These variables contribute to the difference between the theoretical power output and the actual power generated under practical conditions [28], [29].

These findings have significant implications for using renewable energy in aquaponic systems. With a relatively small voltage drop due to temperature increases, monocrystalline solar panels were shown to be efficient enough for use in tropical environments with moderate temperature fluctuations. This increases the potential of this system to be applied in areas with high sunlight intensity, where increasing temperatures can be a challenge in maintaining energy efficiency. In addition, the Arduino-based automation system enables real-time monitoring and control, which improves the system's overall efficiency and minimizes unnecessary energy use.

Table 1. Voltage, current, and light intensity of solar panels

Hours	Voltage (V)	Current (A)	Power (Watt)	E (lux)	Light Intensity (W/m^2)	Temperature (^oC)
07.00	44	0.2	8.8	20,340	160.686	29.90
08.00	42	3.4	13.6	24,500	193.55	31.50
09.00	40	5.1	204.0	30,720	242.688	34.70
10.00	41	6.1	250.1	24,180	191.022	36.40
11.00	26	5.4	140.4	28,690	226.651	37.70

12.00	44	5.1	224.4	43,980	347.442	38.60
13.00	39	6.7	261.3	45,460	359.134	38.20
14.00	46	2.4	110.4	45,720	361.188	38.00
15.00	46	2.0	92.0	39,310	310.549	38.00
16.00	42	1.9	79.8	30,720	242.688	36.00
17.00	41	1,0	41.0	24,500	193.55	35.60
18.00	39	0,1	3.9	20,290	160.291	34.70

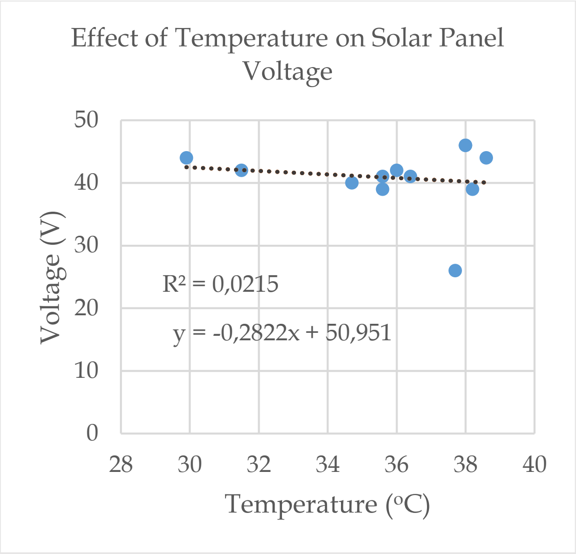

Figure 8. Graph of temperature effect on voltage

Automation testing and monitoring of water spinach plants over 10 days, the growth monitoring system for water spinach plants was tested on two fields. The sensor readings showed an average pH of 5.78 for the first field and 6.12 for the second. The average humidity level was 398.4 for the first field and 492.9 for the second. The average temperature across both fields was approximately 32.07°C. The average increase in plant height was 1.4 cm for the first field height corresponds with an increase in the number of leaves as the plants mature [30].

The watering system for the water spinach plants is automated through a pre-programmed Arduino system as the main controller that reads the time from the RTC (Real Time Clock) module to turn on and off the water pump according to the schedule. RTC provides accurate time data to Arduino through I2C communication. The Arduino is programmed to check the time from the RTC and activate the relay, which functions as an electronic switch. When the time matches the schedule, the Arduino sends a signal to the relay to close the electrical circuit so that the pump turns on and off again after a specific duration. The relay connects the pump to the power source, while the Arduino logic ensures the system runs on schedule and safely. Water is distributed via a pipe system along the planting area, with sprinklers ensuring even coverage. According to the research, the pump used for watering has a power rating of 125 watts, operating for 2 minutes (0.03 hours) per cycle. The electrical energy required to run the pump for each watering session is 3.75 Wh. When the pump runs twice daily, the total electrical energy consumption amounts to 7.5 Wh. Figure 9 provides field documentation of the pump in operation during watering.

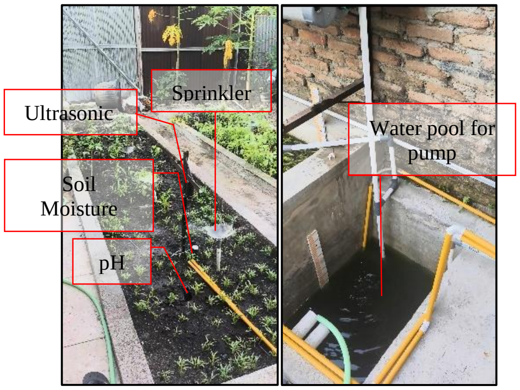

Figure 9. The condition of the land and water source pond when the watering pump is operating

Over a 10-day testing period of the catfish pond automation and monitoring system, the average pH was recorded at 7.60, while the average TDS value was 431.9 ppm. The pond's average temperature was 35.79°C, and the water level dropped between 2 cm and 3 cm per day, from a maximum pond depth of 32 cm. Fish waste, rich in microorganisms and dissolved organic matter, plays a crucial role in promoting the growth of aquaponic plants [31].

The catfish pond's water pump and feeding servo operate using an automated system controlled by an Arduino. The pump is set to run three times daily, at 7:00 AM, 12:00 PM, and 5:00 PM, with each circulation lasting 5 minutes. Meanwhile, the feeding servo is programmed to activate twice daily, at 8:00 AM and 4:00 PM, rotating to a 90-degree angle for 5 seconds during each feeding. According to the research findings, when the circulation pump is activated, the excess pond water exceeding the maximum height flows through two filtration ponds before returning to the pump's water source, as illustrated in Figure 10. The study also determined that the circulation pump for the fish pond uses 115 watts of power for 5 minutes (0.08 hours) per operation. Consequently, the energy consumption for a single cycle is 9.2 Wh. Since the pump operates three times a day, the total daily energy usage amounts to 27.6 Wh.

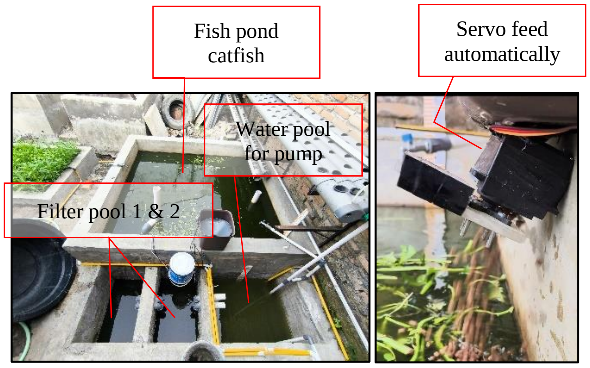

Figure 10. Documentation of automatic feed and circulation pool

The catfish pond automation system uses Arduino as the central controller to turn on and off the water pump for circulation and move the servo for automatic feeding according to the schedule determined by the RTC (Real Time Clock) module. The RTC provides accurate time data to the Arduino via I2C communication, then compared with the schedule. At the appropriate time, the Arduino activates a relay to turn on the water pump and moves the servo to a specific position to open the feed valve, with a PWM signal on the servo pin. After the pump runs for a particular duration, the Arduino switches off the relay to disconnect the electricity to the pump and returns the servo to the starting position to close the valve. The 10-day automation test showed that using the Arduino-based system could maintain the stability of environmental conditions in real-time, contributing to better growth of the water spinach plants with an average height increase of 1.4 cm per day. This shows a better increase in efficiency compared to the non-automated system reported in another study [32], where watering and monitoring needs were done manually. This automated system also significantly reduces human error in aquaponics management, thus optimizing energy and water use. The automated watering system has an average energy consumption for water pumps of 7.5 Wh per day for watering water spinach plants, and 27.6 Wh per day for circulating fish ponds, much lower than manual systems that are typically not optimized for energy use. This shows that the use of renewable energy-based automation in aquaponics can reduce operational costs and overall environmental impact, which is crucial in realizing sustainable agriculture

In calculating the efficiency of the solar panel and the operational cost of the aquaponic system, tests conducted between 07:00 and 18:00 recorded an average voltage of 48.83 V, an average current of 3.28 A, and an average light intensity of 249.1199 W/m². This experiment utilized two 200 Wp solar panels connected in series, resulting in a total surface area of 1.0184 m². The standard efficiency of the solar panels was then determined using the equations provided in formulas (1) and (2).

$$P_{in} = 249.1199 W/m^2 \times 1.0184 m^2$$

$$P_{in} = 253.70 Watt$$

$$FF = \frac{V_{\max} \times I_{\max}}{V_{oc} \times I_{sc}} = \frac{45.6 \times 4.39}{52.96 \times 4.94} = 0.77$$

$$P_{out} = 40.83 \times 3.28 \times 0.77$$

$$P_{out} = 103.12 Watt$$

The results of the calculation output and input power on solar panels can be used to calculate the efficiency of solar panels.

$$\eta = \frac{103.12 Watt}{253.70 Watt} \times 100\%$$

$$\eta = 40.65\%$$

This study used 2 (two) 100 Wp monocrystalline solar panels or a total power of 200 Wp arranged in series, resulting in a solar panel efficiency of 40.65%. This efficiency value exceeds the average efficiency of a solar panel, where the average efficiency of a solar panel generally ranges from 12-19%, depending on the type of panel and the materials used in its manufacture. Different solar panels will have different efficiency levels [33]. During the monitoring of the aquaponic system, it was observed that the daily energy consumption reached 89.9 Wh, which when combined with the energy required for automatic watering and circulation pumps, the total daily energy use reached 125 Wh. Given that the battery has a capacity of 1200 Wh, if in some period of, for example, three to five days there is no or lack of charging by the solar panel due to unfavorable weather, the solar power system developed in this study is still able to supply enough electricity to power the aquaponics system for those few days.

A cost-efficiency analysis was performed using the Levelized Cost of Energy (LCOE) approach to assess and compare the cost-effectiveness of solar power plants versus PLN power plants. The LCOE method offers insight into the cost per unit of energy generated by a particular resource throughout its operational lifespan. Given that the PLN tariff is fixed, the LCOE for PLN equals the tariff for the 1300-watt category, which is Rp1,444.70 per kWh. The total upfront investment cost (CapEx) for the solar panel system is Rp 5,023,500. Solar power plants ' annual operation and maintenance expenses (OpEx) typically range from 1-2% of the CapEx [34]. Based on this, the study uses a 1% OpEx rate, and with a 25-year lifespan for the solar panels, the total OpEx over 25 years amounts to Rp 50,235 per year, or Rp 1,255,875 in total. Adding this to the initial CapEx, the total cost becomes Rp 5,023,500 + Rp 1,255,875 = Rp 6,279,375. The annual energy output of the solar panels is 1000 Wh/day, resulting in 365 kWh per year. Over 25 years, the total energy production is 25 x 365 kWh = 9,125 kWh. Therefore, the LCOE for the solar panels can be calculated using formula (3).

$$LCOE = \frac{Rp6,279,375}{9,125kWh} = Rp\,688.15/kWh$$

The LCOE for PLN is IDR 1,444.70/kWh, while it is IDR 688.15/kWh for the solar panel system. Using the PLN tariff of IDR 1,444.70/kWh, the daily cost of powering the aquaponic system with PLN electricity is calculated as 0.125 kWh x IDR 1,444.70/kWh = IDR 180.59, leading to an annual cost of IDR 180.59 x 365 = IDR 65,947.35. In contrast, the daily cost of running the water pump using solar energy is 0.125 kWh x IDR 688.15/kWh = IDR 86.02, with an annual cost of IDR 86.02 x 365 = IDR 31,397.30. Therefore, it can be concluded that the solar panel system offers greater cost efficiency compared to using electricity from PLN. The cost-efficiency of solar panels shows great potential for reducing the long-term cost burden of operating renewable energy-based aquaponics systems while supporting sustainability and environmental friendliness.

Although Arduino-based automation systems can reduce human intervention and improve operational reliability, this study did not directly explore the effect of automation on energy efficiency. Further studies should explore the energy efficiency gains achieved through advanced automation techniques, such as pump voltage regulation or dynamic scheduling based on real-time sensor data.

Conclusion

This study successfully incorporated solar panels as an alternative energy source for an automated aquaponic system monitored with Arduino technology. The analysis revealed that the 200 Wp solar panel system was sufficient to meet the daily energy requirement of 125 Wh, which powers two water pumps and the monitoring system. The solar power system demonstrated a lower cost per unit of energy than existing PLN electricity rates, offering financial benefits while reducing environmental impact, making it a sustainable solution for powering aquaponic systems. The Arduino-based automation system proved effective in optimizing operations by reducing human intervention and enhancing system reliability, with sensors delivering real-time, precise data critical for maintaining optimal water quality and ensuring the well-being of both fish and plants. In conclusion, integrating microcontrollers and renewable energy in aquaponic systems offers numerous benefits and holds potential for future advancements.

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References

[1] R. E. S. Dauhan and E. Efendi, “Efektifitas sistem akuaponik dalam mereduksi konsentrasi amonia pada sistem budidaya ikan,” *E-Jurnal rekayasa dan teknologi budidaya perairan*, vol. 3, no. 1, pp. 297–302, 2014.

[2] N. F. Farida, S. H. Abdullah, and A. Priyati, “Analisis kualitas air pada sistem pengairan akuaponik [analysis of water quality in Aquaponic Irrigation System],” *Jurnal Ilmiah Rekayasa Pertanian dan Biosistem*, vol. 5, no. 2, pp. 385–394, 2017.

[3] Y. Rahmanto, A. Burlian, and S. Samsugi, “Sistem Kendali Otomatis Pada Akuaponik Berbasis Mikrokontroler Arduino Uno R3,” *Jurnal Teknologi Dan Sistem Tertanam*, vol. 2, no. 1, pp. 1–6, 2021, doi: https://doi.org/10.33365/jtst.v2i1.975.

[4] S. Goddek, B. Delaide, U. Mankasingh, K. V. Ragnarsdottir, H. Jijakli, and R. Thorarinsdottir, “Challenges of sustainable and commercial aquaponics,” *Sustainability*, vol. 7, no. 4, pp. 4199–4224, 2015.

[5] Y. Chandra, “Perancangan Pembangkit Listrik Tenaga Surya (PLTS) Sebagai Sumber Energi Listrik Untuk Akuaponik,” *Electrical Network Systems and Sources*, vol. 1, no. 1, pp. 19–24, 2022.

[6] T. F. Andansari, M. A. Habibi, I. Alfianto, S. N. Maharani, M. Yazid, and A. Wibawa, “Instalasi plts hybrid untuk akuaponik Sengkaling,” *at-tamkin: Jurnal Pengabdian kepada Masyarakat*, vol. 5, no. 2, pp. 24–37, 2022.

[7] B. Hartono and Purwanto, “Perancangan Pompa Air Tenaga Surya Guna Memindahkan Air Bersih ke Tangki Penampung,” *Jurnal Ilmiah Teknik Mesin*, vol. 9, no. 1, pp. 28–33, 2015.

[8] Y. P. Efendy, D. Y. Qadlizaka, R. R. Raihanfalaach, and N. Azizah, “Penerapan Teknologi Budidaya Akuaponik Sebagai Bentuk Pemanfaatan Lahan Sempit di Kelurahan Jambangan, Surabaya,” *KARYA UNGGUL-Jurnal Pengabdian Kepada Masyarakat*, vol. 1, no. 2, pp. 62–68, 2022.

[9] Z. Hasan, Y. Andriani, Y. Dhahiyat, A. Sahidin, and M. R. Rubiansyah, “Growth of different strains of three fishes and water spinach (Ipomoea reptans Poir) based aquaponic,” *J Iktiologi Indones*, vol. 17, no. 2, pp. 175–184, 2017.

[10] R. A. Nugroho, L. T. Pambudi, D. Chilmawati, and A. H. C. Haditomo, “Aplikasi teknologi aquaponic pada budidaya ikan air tawar untuk optimalisasi kapasitas produksi,” *Jurnal saintek perikanan*, vol. 8, no. 1, 2012.

[11] L. E. Rahmadhani, L. I. Widuri, and P. Dewanti, “Kualitas mutu sayur kasepak (kangkung, selada, dan pakcoy) dengan sistem budidaya akuaponik dan hidroponik,” *Jurnal Agroteknologi*, vol. 14, no. 01, pp. 33–43, 2020.

[12] M. I. Nasution, L. H. Lubis, and W. U. A. Ritonga, “Implementasi Mikrokontroler Berbasis IoT untuk Optimalisasi Kinerja Sistem Akuaponik,” *Phi: Jurnal Pendidikan Fisika dan Terapan*, vol. 9, no. 1, pp. 7–14, 2023.

[13] D. Karimanzira and T. Rauschenbach, “Optimal utilization of renewable energy in aquaponic systems,” *Energy Power Eng*, vol. 10, no. 06, pp. 279–300, 2018.

[14] N. Huda, “Energi Baru Terbarukan Solar Cell Sederhana Untuk Sistem Penerangan Rumah Tangga,” *Cahaya Bagaskara: Jurnal Ilmiah Teknik Elektronika*, vol. 3, no. 1, pp. 6–10, 2018.

[15] M. Djamin, “Penelitian penerapan pembangkit listrik tenaga surya dan dampaknya terhadap lingkungan,” *Jurnal Teknologi Lingkungan*, vol. 11, no. 2, pp. 221–225, 2010.

[16] B. H. Purwoto, J. Jatmiko, M. A. Fadilah, and I. F. Huda, “Efisiensi penggunaan panel surya sebagai sumber energi alternatif,” *Emitor: Jurnal Teknik Elektro*, vol. 18, no. 1, pp. 10–14, 2018.

[17] H. B. Nurjaman and T. Purnama, “Pembangkit Listrik Tenaga Surya (PLTS) sebagai solusi energi terbarukan rumah tangga,” 2022, *Nov*.

[18] N. Arif, S. Suaedi, M. Rahmadi, and F. M. Siregar, “Potensi Energi Surya sebagai Energi Listrik Alternatif berbasis RETScreen di Kota Palopo, Indonesia,” *Dewantara Journal of Technology*, vol. 1, no. 1, pp. 38–42, 2020.

[19] H. Asy’ari, A. Rozaq, and F. S. Putra, “Pemanfaatan Solar Cell dengan PLN Sebagai Sumber Energi Listrik Rumah Tinggal,” *Emitor*, vol. 14, no. 01, pp. 33–39, 2014.

[20] A. B. Karaveli, U. Soytas, and B. G. Akinoglu, “Comparison of large-scale solar PV (photovoltaic) and nuclear power plant investments in an emerging market,” *Energy*, vol. 84, pp. 656–665, 2015.

[21] E. B. Agyekum, V. I. Velkin, and I. Hossain, “Sustainable energy: Is it nuclear or solar for African Countries? Case study on Ghana,” *Sustainable Energy Technologies and Assessments*, vol. 37, p. 100630, 2020.

[22] Krismadinata, Aprilwan, and A. B. Pulungan, “Rancang Bangun Sistem Monitoring Simulator Modul Surya,” *Prosiding - Seminar Nasional Teknik Elektro UIN Sunan Gunung Djati Bandung*, no. Seminar Nasional Teknik Elektro UIN Sunan Gunung Djati Bandung (SENTER 2018), pp. 192–201, 2018.

[23] I. Usman, “Penumbuhan Lapisan Tipis Silikon Amorf Terhidrogenasi Dengan Teknik HWC-VHF-PECVD dan Aplikasinya Pada Sel Surya,” *Bandung: Institut Teknologi Bandung*, 2006.

[24] R. A. M. Napitupulu, S. Simanjuntak, and S. Sibarani, “Pengaruh Material Monokristal dan Polikristal Terhadap Karakteristik Sel Surya 20 Wp dengan tracking sistem Dua Sumbu,” *LPPM Universitas HKBP Nommensen Medan*, 2017.

[25] J. Hernández-Moro and J. M. Martinez-Duart, "Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution," *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 119–132, 2013.

[26] Z. Iqtimal, I. D. Sara, and S. Syahrizal, "Aplikasi sistem tenaga surya sebagai sumber tenaga listrik pompa air," *Jurnal Komputer, Informasi Teknologi, dan Elektro*, vol. 3, no. 1, 2018.

[27] D. Dahliya, S. Samsurizal, and N. Pasra, "Efisiensi panel surya kapasitas 100 wp akibat pengaruh suhu dan kecepatan angin," *Sutet*, vol. 11, no. 2, pp. 71–80, 2021.

[28] A. Asrori and E. Yudiyanto, "Kajian Karakteristik Temperatur Permukaan Panel Terhadap Performansi Instalasi Panel Surya Tipe Mono dan Polikristal," *FLYWHEEL: Jurnal Teknik Mesin Untirta*, vol. 1, no. 1, pp. 68–73, 2019.

[29] Y. I. Lukmato, Muhammad Jubran Rizqullah, Mohamad Wahyu Hidayat, and Siti Diah Ayu Febriani, "Analisis Losses Daya Sel Surya dalam Fabrikasi Modul Surya Monocrystalline 330Wp Pt Santinilestari Energi Indonesia," *Jurnal Inovasi Teknologi Manufaktur, Energi dan Otomotif*, vol. 1, no. 1, pp. 37–44, 2022, doi: 10.57203/jinggo. v1i1.2022.37-44.

[30] S. Rizal, "pengaruh Nutrisi Terhadap Pertumbuhan Tanaman Sawi Pakcoy (Brasicca rapa L.) yang di Tanam Secara Hidroponik," *Sainmatika*, vol. 14, no. 1, pp. 38–44, 2017.

[31] B. Delaide, S. Goddek, J. Gott, H. Soyeurt, and M. H. Jijakli, "Lettuce (Lactuca sativa L. var. Sucrine) Growth Performance in Complemented Aquaponic Solution Outperforms Hydroponics," *Water (Switzerland)*, vol. 8, no. 10, pp. 1–11, 2016, doi: 10.3390/w8100467.

[32] L. H. Pratopo and A. Thoriq, "Produksi Tanaman Kangkung dan Ikan Lele dengan Sistem Akuaponik," *Paspalum: Jurnal Ilmiah Pertanian*, vol. 9, no. 1, pp. 68–76, 2021.

[33] D. Dahliya, S. Samsurizal, and N. Pasra, "Efficiency of a 100 Wp Capacity Solar Panel Due to the Effect of Temperature and Wind Speed," *Jurnal Ilmiah SUTET*, vol. 11, no. 2, pp. 71–80, 2021.

[34] S. G. Ramadhan and C. Rangkuti, "Perencanaan Pembangkit Listrik Tenaga Surya Di Atap Gedung Harry Hartanto Universitas Trisakti," in *Prosiding Seminar Nasional Cendekiawan*, 2016, pp. 21–22.