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Implementation of Solar Driven Aquaponics Model for Energy Efficient Urban Farming

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Abstract

This project implemented a solar-driven aquaponics system to solve the problems of managing resources and energy in urban farming. The main objective was to combine aquaculture and hydroponics into an automated name aquaponics system. The system that runs on renewable energy to reduce its impact on the environment and reliance on the grid. The system used an ESP32 microcontroller and different IoT sensors to monitor the pH, water level, temperature, and humidity in real time. It used a 200-liter fish tank and a media grow bed. A 12V battery and a 50W monocrystalline solar panel was used to provide power. The results showed that the system worked well on solar power and kept a healthy symbiotic environment, which helped plants grow steadily and fish survive well. The project finds that aquaponics powered by solar energy is a long-term solution for food security in cities. Suggestions for future development include making the battery storage bigger, adding lights for plants to grow, and making the design bigger so it can be used by the whole community.

1. Introduction

Aquaponics first appeared in 1930s in the North Kerian in Perak, the fish were cultivated in rice field as a rice fish farming systems. This is used nutrient rich water to support both fish and rice production. Today there are now stablished the basic concept by combining aquaculture and agriculture. The earlier developments are observed in 1920, which is when Malaysia practices polyculture of chines carps in former mining ponds [1].

The development of modern aquaponics in Malaysia was later strengthened through academic research and experimental programs. University was very important in making aquaponics a formal practice. For instance, University Malaysia Kelantan investigated whether aquaponic systems that grow lettuce and catfish would work. The goal of these studies was to help low-income families, and one of the things they investigated was aquaponics to reduce poverty [2].

Aquaponics was considered at as a long-term farming method that combined aquaculture and hydroponics. Aquaculture was the term for farming fish in a controlled body of water. Hydroponics is the process of growing plants without soil by using water that is full of nutrients. This system used fish waste as food for plants. It cut down on water use and got rid of chemical fertilisers. But traditional aquaponics systems depended a lot on grid electricity for pumps and monitoring.

This study was necessary to reduce dependency on conventional electricity in aquaponics systems. High energy use raised operating costs and made it hard to use the system in urban and remote areas. Solar energy has

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been demonstrated to be a renewable energy source that could keep things running all the time. To make the system more efficient and reliable, automation and monitoring were needed.

A solar driven aquaponics system needs continuous water circulation and aeration for fish growth and plants. This approach was especially beneficial in area without access to grid electricity. The solar energy was utilized to operate water pumps and monitoring devices in an environmentally friendly manner. As a result, the system supported smart farming practices while reducing environment impact [5].

Manual monitoring of aquaponics system often led to human error because it required significant time and effort to make it. the critical changes in water quality parameters such as Ph, ammonia, oxygen and nutrient level are sometimes overlooked. These fluctuations increased the risk of fish and plant diseases and could cause system failure. The resulting stress negatively affected growth performance. Since manual methods relied mainly on visual inspection and periodic sampling, they lacked real-time data and continuous monitoring, making it difficult to detect and respond promptly to harmful conditions [6].

Urban solar driven aquaponics system faced challenges due to high energy consumption during the operation. The continuous operation of water circulation pumps, oxygen and temperature control was necessary to maintain suitable conditions for fish and plants Although solar energy was a renewable resource, its intermittent nature and limited capacity often prevented it from fully meeting system demands, especially for cooling in hot climates. This situation required the use of backup power sources such as grid electricity or fossil fuels, which increased operational costs and carbon emissions. Therefore, the sustainability goals of urban farming was needed which to improve the efficiency and sustainability, energy efficiency, advanced energy management and hybrid renewable energy solutions.

2. Methodology

The main goal of this project is to build a solar-powered aquaponic system that makes urban farming easier and more environmentally friendly. The goal is to make a system where fish and plants can live together in a balanced way that doesn't need any outside help. The plants get nutrients from the fish waste, and the plants clean the water for the fish in return. Solar panels are the main source of power for the system. The methodology includes picking the right material, designing system and putting sensors to keep monitor the water quality, temperature pH value. this step-by-step method is to make sure the system works well and energy efficiency is suitable for urban farming.

2.1 Project Flowchart

This flowchart represents a monitoring and control system which is for automated Aquaponic system that integrates with the mobile application. It begins with the system initialization where the first attempts are to connect it with Wi-Fi. Once it is connected, it proceeds to establish a connection with data communication.

After successfully completing the communication setup, the system continuously reads the sensor data. It evaluates the input to determine the specific conditions for water level, pH values, water temperature and Humidity. Based on the reading the system will check if the threshold value is met. If the conditions indicate that water is needed. It sends a notification to mobile app then activate the pump. If not, the pump will remain off, and the user will be notified accordingly.

The additional sensor data or other system outputs are handled. The temperature and humidity levels are evaluated to determine whether they are within acceptable limits. If the values are outside the specified range, alerts are sent to the mobile application. The process is then looped back to continue monitoring until all parameters are within satisfactory limits.

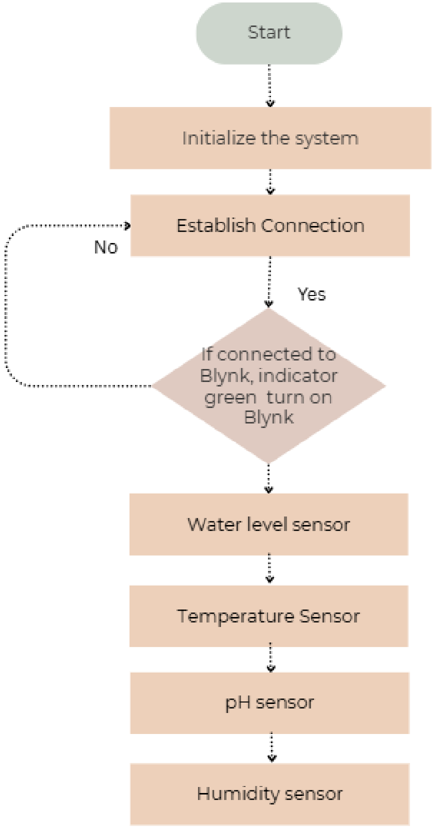

Fig. 1 System Connection

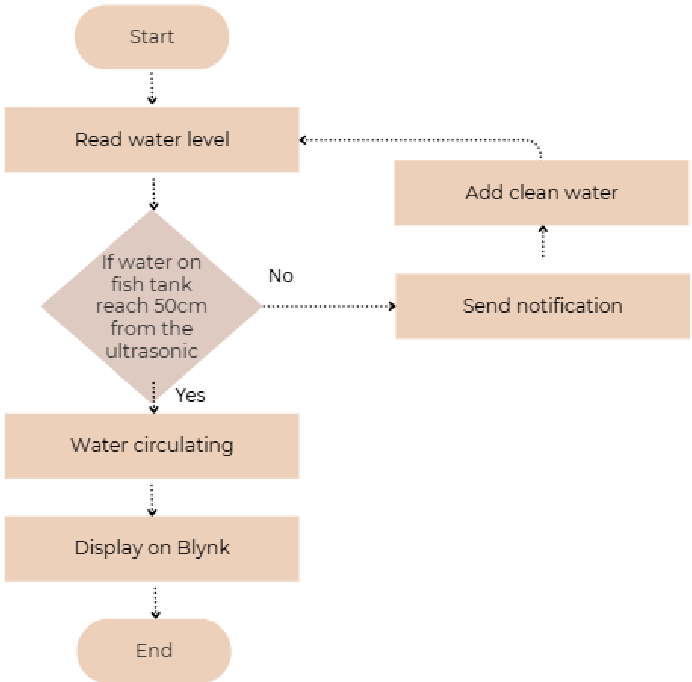

Fig. 2 Water level control flowchart

The water level control is implemented for the fish tank. When a low water level is detected in the tank, a notification is sent to the Blynk application. The tank is then required to be filled by the user until the specified high level or preset values is reached. The sensor continuously notifies the user by sending alerts to the smartphone whenever a low water level is detected. The water is top up manually by the user.

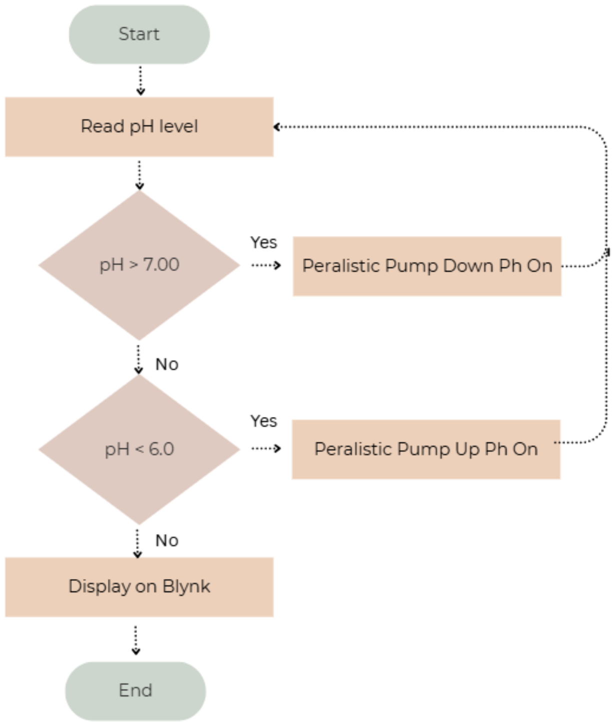

Fig. 3 pH level sensor

When the pH value is higher and lower within the range the peristaltic pump will turn on to neutralize the pH value with the pH solution for getting the value than suitable for the plants.

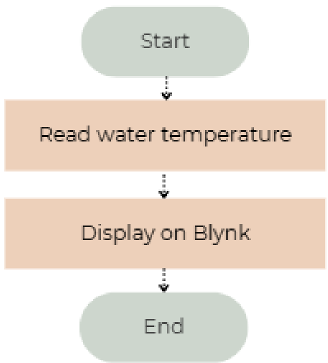

Fig. 4 Water temperature

The water temperature sensor will sense the temperature on the fish tank and display on the blynk for user to monitor.

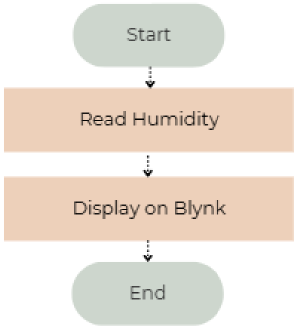

Fig. 5 Humidity sensor

2.2 Block Diagram

This block diagram represents the automatic system for aquaponic system using solar driven. It begins with the sunlight which gives energy to the solar panel for generating electricity. This power goes through a charge controller that manages the flow of electricity into a battery, ensuring safe and efficient charging. The battery will store energy for continuous use even if there is no sunlight. Then the step-down converter will step down the voltage for supplying the load which includes various components of aquaponic system. For powering the DC water pump is hybrid, it can be powered up using battery and electrical grid which is socket outlet. Socket will connect to the socket outlet and goes to the AC to DC power supply then goes to the relay to power the water pump.

The system's main component is ESP32 microcontroller, this smart controller collects data from various sensors and controls the device accordingly. It also monitors water temperature in the fish tank; by using that data it manages the environment for aquatic life.

The ESP32 also receives input from a humidity and temperature sensor, which maintains the ideal condition around the plants. A pH sensor will monitor the acidity or alkalinity of water in the system, which is very important for both fish and plant health. The camera is used for users to monitor fish and plant whenever there is ready to be harvested.

The water from the fish tank is pumped by a water pump to the grow bed where the grow bed also acts as a filter for the fish tank using the hydrokorrel ball, where they convert fish waste (ammonia) into nitrates, which are then absorbed by the plants as fertilizer. The fish tank is subsequently filled with this purified and enhanced water, therefore establishing an environmentally friendly cycle. A smartphone receives all this data so that users may remotely monitor and operate the machine using Blynk apps

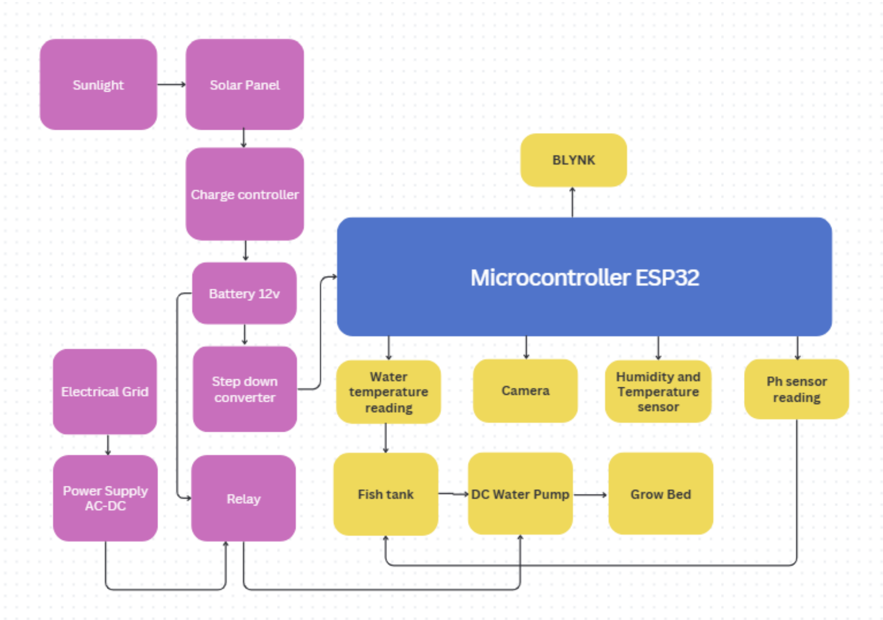

Fig. 6 Block Diagram

2.3 Schematic Diagram

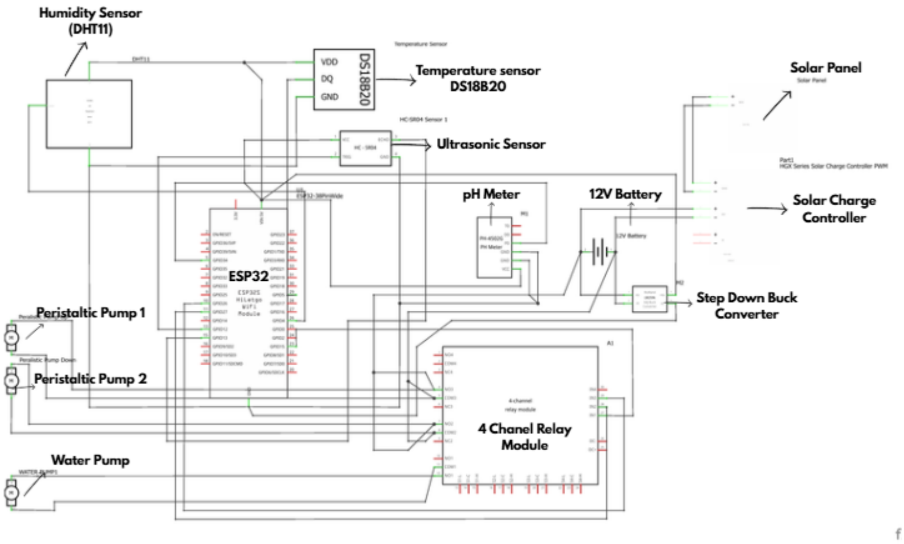

Fig. 7 Schematic diagram

The ESP32 microcontroller is used to control and measure an integrated fish-plants environment in the solar-powered aquaponics system. It measures temperature and humidity using a DHT11 sensor to control plant conditions, A pH sensor monitors the water quality of the fish tank, and an ultrasonic sensor monitors the water level in fish tank then sent via the Blynk app. The two peristaltic pumps are used to pump a Ph solution to maintain the ph in the fish tank. The 12V water pump is used to circulate water are one from nutrient water in the fish tank to the plants, and recirculates filtered water back into the tank, both relay-controlled and linked to the microcontroller. The system operates automatically and transmits real-time data and alerts through the Blynk app through Wi-Fi and is powered renewable by a solar system.

2.4 3D Layout Design

This 3D design was design using AUTOCAD 3D software.

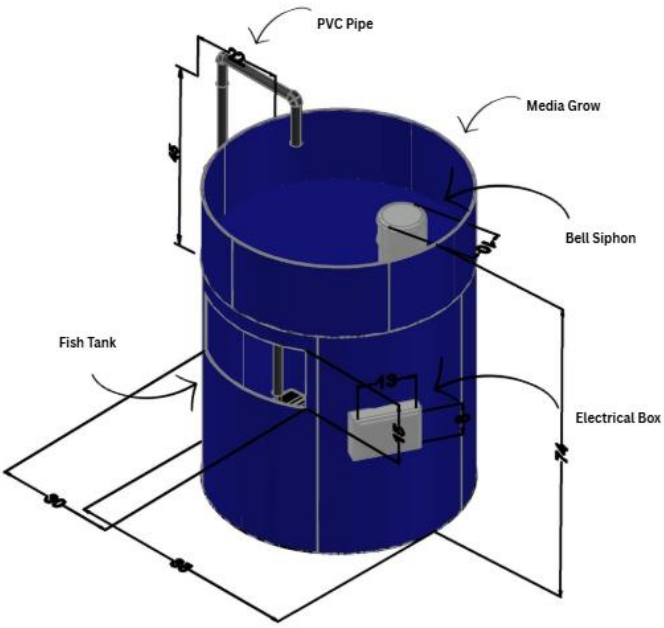

Fig. 8 Project view

3. Result and discussion

This chapter talks about the results of developing and testing the solar-powered system for monitoring and controlling aquaponics. We check how well the system works by looking at real-time data from the solar charging unit, battery, sensors, and actuators while the system is working. The major point of this chapter is to look at how well the renewable energy supply works, how stable the system is, and how well the parts that keep an eye on things work.

The first thing the study does is look at how well the solar charging battery works by looking at how the voltage, current, and power fluctuate over time. Next, they look at how the battery discharges while the system is running. We make sure that the sensor data for pH level, water temperature, air temperature, and humidity are correct and consistent so that they may be used to control the environment in aquaponics. Also, the DC water pump and peristaltic pumps are tested to make sure they are working right, keeping the water moving, and keeping the pH level consistence.

There are tables and graphs for all of the trial outcomes so that you can easily see what they signify. The sessions explain how the system works in real life and how it helps aquaponics applications reach their goals of using energy in a way that is good for the environment, automating tasks, and keeping an eye on things in real time.

3.1 System power consumption analysis

The total power consumption of the aquaponic system were determined based on the electrical specification of each electronic component used. In the system consist of an ESP32 as a microcontroller, relay module, servo motor for fish feeding mechanism, ultrasonic sensor as water level sensor, peristaltic pump for neutralize the pH in the fish tank, pH sensor, temperature sensor and humidity sensor.

3.2 Daily energy consumption

This section presents the daily energy consumption of the solar-driven aquaponics system. The total energy usage of each system component is calculated based on its rated power and operating duration using the relationship $E = P \times t$. The calculated daily energy consumption of all components is summarized in Table 4.4, including the ESP32 controller, sensors, relays, servo motor, and peristaltic pumps. The overall daily energy requirement of the system is determined to assess the suitability of the solar power supply and battery capacity.

$$E = P \times t \tag{3.2}$$

E is energy consumption (Wh)
P is power (W)
T is operating time (h)

Table 1 : Daily energy consumption

Component	Energy (Wh/day)
ESP32	**19.9**
Sensor and Relay	**18.6**
Servo motor	**0.025**
Peristaltic Pump Up	**36**
Peristaltic Pump Down	**36**
Total Energy Consumption	**110.53**

3.3 Solar panel sizing

Malaysia receive an average of 4 to 5 peak sun hours per day. The system losses such as battery charging inefficiency, wiring loss and controller loss, a total system efficiency of 70% was assumed.

$$P_{panel} = \frac{E_{daily}}{H \times \eta} \tag{3.3}$$

Where
E_{daily} = daily energy consumption (Wh)
H = peak sun hours (h)
η = system efficiency

Based on the calculations, the minimum of 39.475W solar panel was required. However, to ensure stable operation during cloudy days and to allow future system expansion, a 50W monocrystalline solar panel was selected.

4. Battery Performance Analysis under Solar Charging and Load Conditions

This section describes the battery charging performance using a solar panel. The charging process is evaluated by measuring the battery voltage, charging current, and output power at 30-minute intervals between 11.00 a.m. and 1.00 p.m. The collected data, as presented in Table 2, is used to observe the variation in charging characteristics under changing solar conditions. The results provide an understanding of how solar energy availability influences the battery charging behavior throughout the charging period.

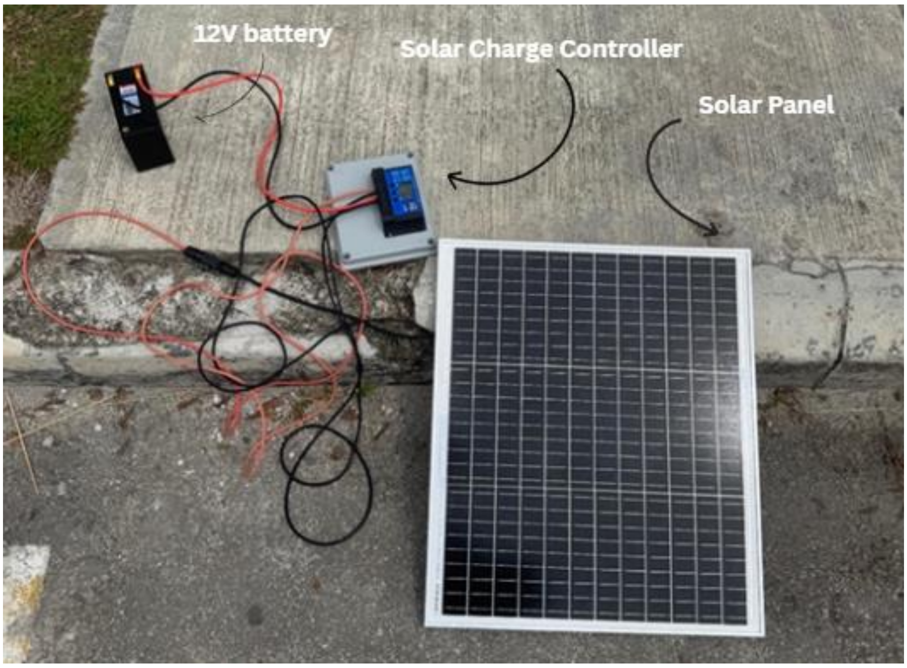

Fig. 9 Battery Charging Using Solar Energy

Table 2 Battery Charging Characteristics Using Solar Energy

Time	Voltage (V)	Current (A)	Power (W)
11.00am	12.8	1.04	13.3
11.30am	13.07	1.36	17.77
12.00pm	13.28	0.61	8.1
12.30pm	13.21	0.89	11.75
1.00pm	13.14	0.7	9.2

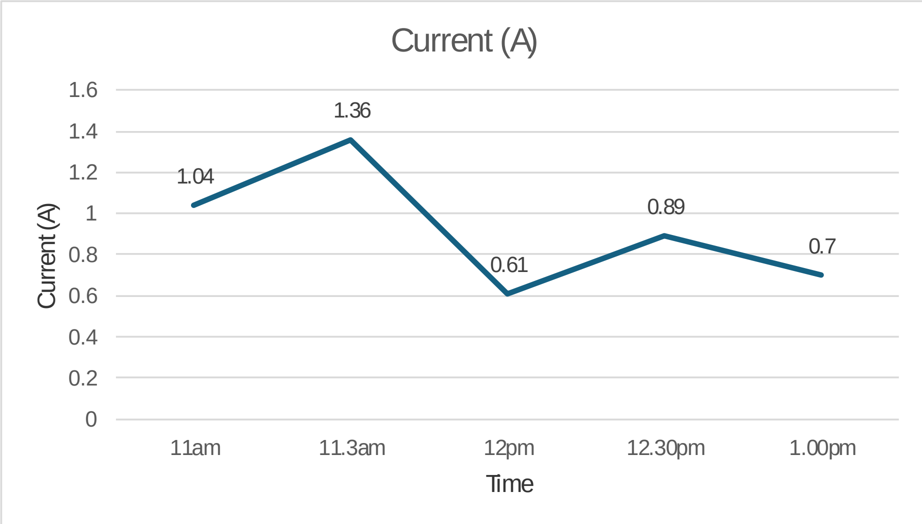

Fig 10 Current vs Time

The current vs time graph shows the variation of charging current supplied by the solar panel to the battery in 2 hours which is from 11.00am to 1.00pm. At 11.00am the charging current starts at 10.4A indicating sufficient solar irradiance for battery charging. The current then increase to a peak value of 1.36A at 11.30am. which the highest solar intensity during the test. At 12.00 pm the current drops significantly to 0.61A which is most likely caused by temporary reduction in solar irradiance, such as cloud cover. Then the current recover to 0.89 at 12.30pm showing the improve sunlight condition, finally at 1.00opm the current slightly decrease to 0.70A which indicating reduction of solar intensity.

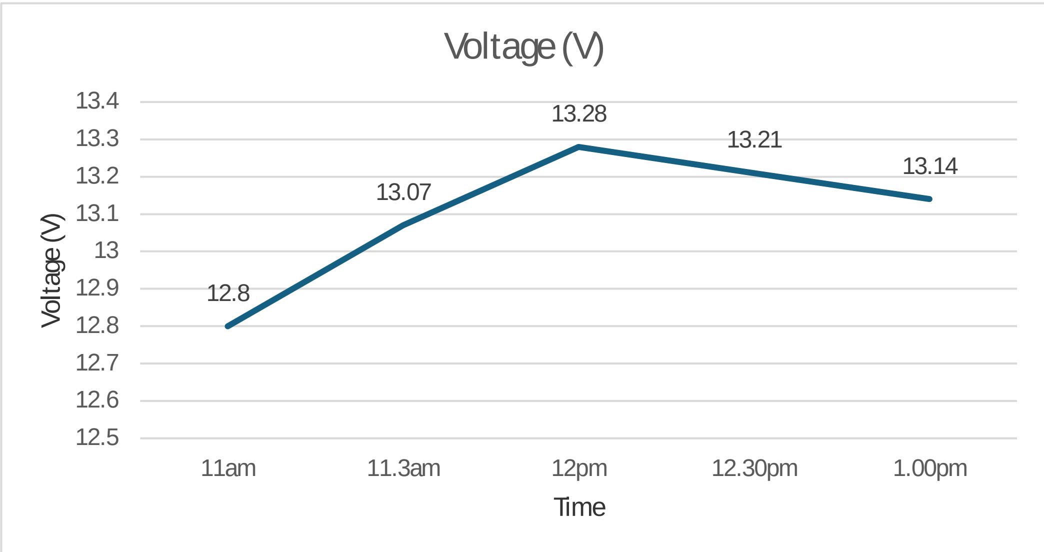

Fig. 11 Voltage vs Time

The voltage vs time graph illustrates the battery behaviour during the solar charging process. At 11.00am the battery voltage is 12.8V which indicates the charge state of the battery. The voltage then increases steadily to 13.07V at 11.30am and reaches a maximum of 13.28V at 12.00pm. this shown the battery is actively charging. after 12.00pm the voltage slightly decreases to 13.21V at 12.30pm and 13.14V at 1.00pm. in addition, the voltage shows the safe charging range for 12V, which is stable

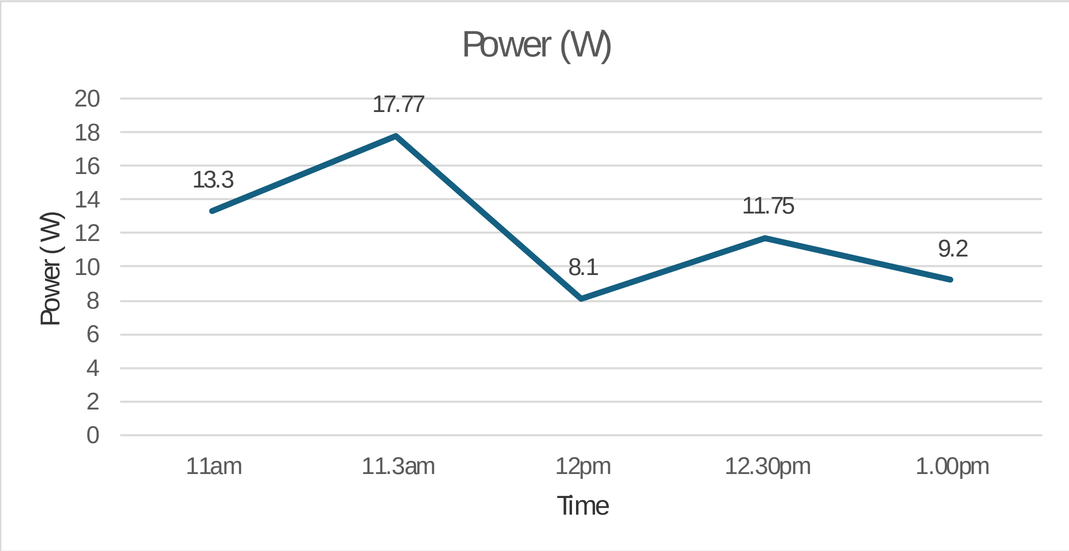

Fig. 12 Power vs Time

The power vs. time graph shows how much electrical power is going to the battery. This is based on the voltage and current that were measured. The charging power is 13.3W at 11:00 AM and goes up to 17.7W at 11:30 AM. This peak power happens when the battery voltage rises and the charging current rises. The power reduces drastically to 8.1W at noon, which is less than what was reported before. Then, at 12:30 p.m., it goes back up to 11.75W before going down to 9.2W at 1:00 p.m.

4.1 Discharging performance

This section presents the battery discharge characteristics under continuous sensor load conditions without the operation of the DC water pump. The battery performance is evaluated by monitoring the voltage, current, and power output over a 7-hour period. The measured data, as summarized in Table 4.8.2, are used to observe the discharge behavior and assess the stability of the battery in supplying power to the sensors during continuous operation.

Table 3 Battery Discharge Under Continuous Sensor Load

Time (Hours)	Voltage (V)	Current (A)	Power (W)
0	12.4	0.26	3.22
1	12.38	0.25	3.1
2	12.38	0.26	3.22
3	12.3	0.24	2.9
4	12.3	0.26	3.2
5	12.2	0.29	3.6
6	12.2	0.25	3.05
7	12.1	0.25	3.02

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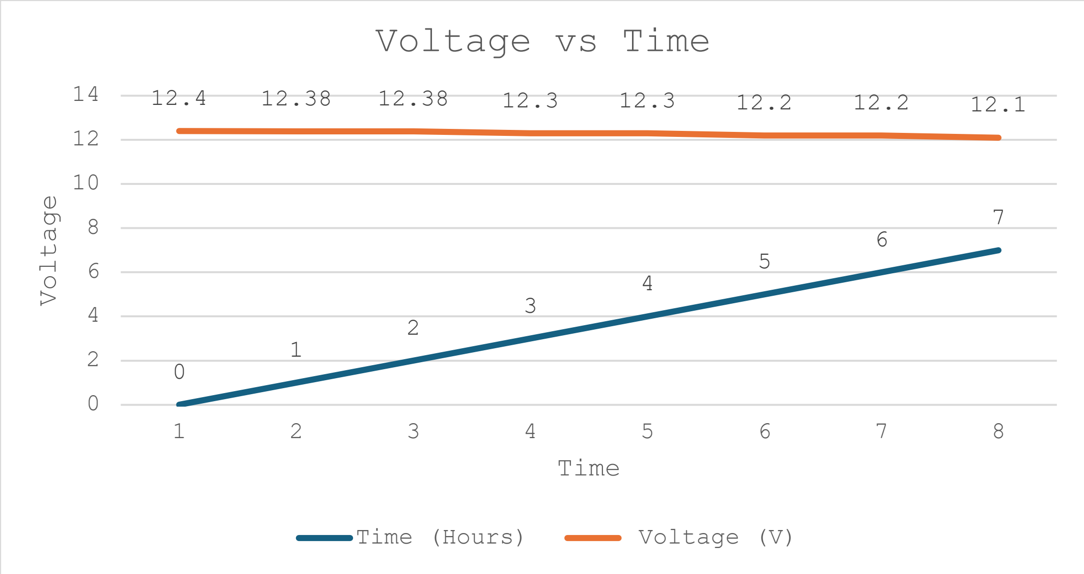

Fig. 13 Voltage vs Time

The battery voltage was observed to decrease gradually from 12.4 V at hour 0 to 12.1 V at hour 7, as indicated by the results. No sudden voltage drop was recorded during the testing period. Instead, a slow and steady voltage reduction was observed, indicating a stable and healthy energy profile. This behavior demonstrates that the battery was discharged safely, and that continuous operation of the aquaponics system could be maintained.

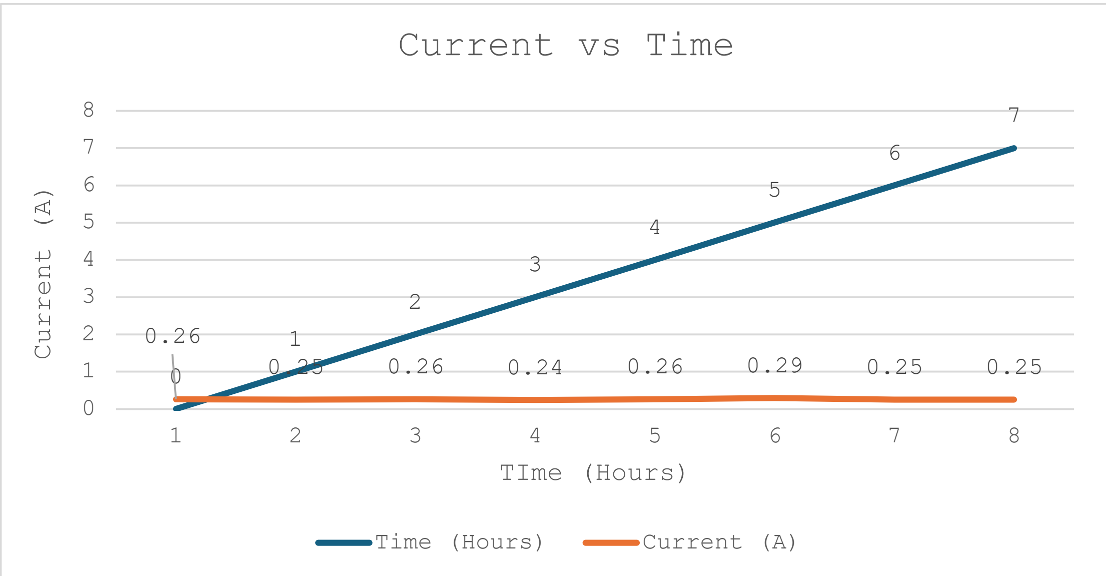

Fig. 14 Current vs Time

The average measured current was 0.26 A, with a range of 0.24 A to 0.29 A. The current changes a little bit, especially around hour five when it went up to 0.29 A. This change is caused by the fact that the peristaltic pumps only turn on when the pH goes below 6 or above 9. When the system is in monitoring mode, it uses less current than usual.

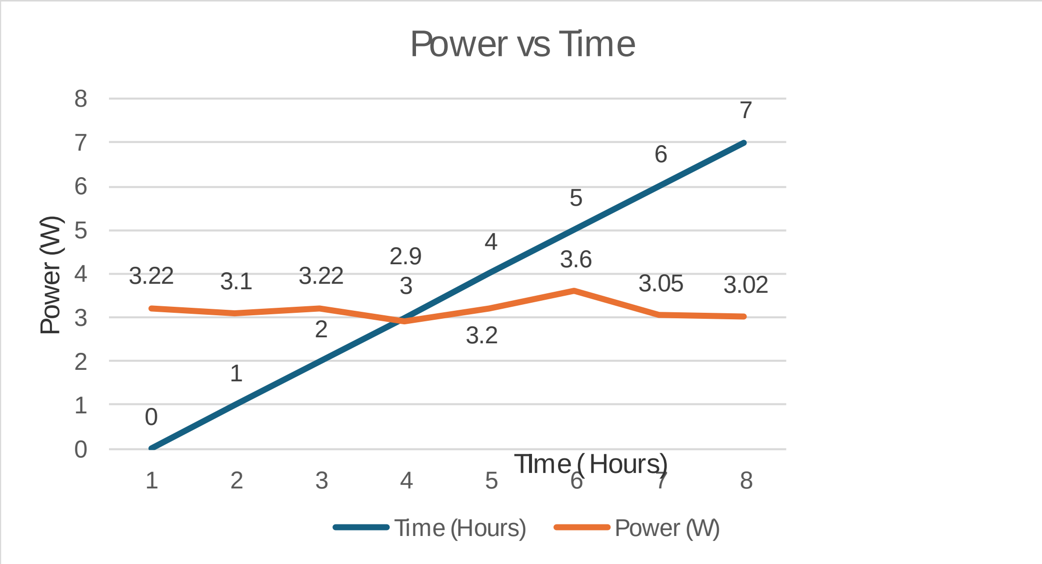

Fig. 15 Power vs Time

With testing range from 2.9 W to a maximum of 3.6 W, the data shows a steady power consumption throughout the 7-hour testing period. This small variation shows that the system or device under stress maintains a steady energy demand, which is crucial for stability or battery efficiency. At the five-hour mark, there is a small peak in power demand which may indicate a brief spike in workload or a shift in the power converter's efficiency as components reached their operating temperature. The power draw is consistent throughout the test, averaging roughly 3.17 W despite this slight variation.

4.2 DC water pump discharging

This section presents the battery discharge characteristics under DC water pump load conditions. The battery performance is evaluated by monitoring the voltage, current, and power output while the DC water pump is in operation. The measurements, as summarized in Table 4, are recorded at specific time intervals to analyze the effect of the pump load on the battery discharge behavior and overall system performance.

Table 4 Battery Discharge Characteristics Under DC Water Pump Load

Time	Voltage (V)	Current (A)	Power (W)
11.25am	11.80	1.69	19.94
11.55am	11.40	1.67	19.09
12.25pm	10.50	1.35	14.20
12.55pm	7.12	0.84	5.98

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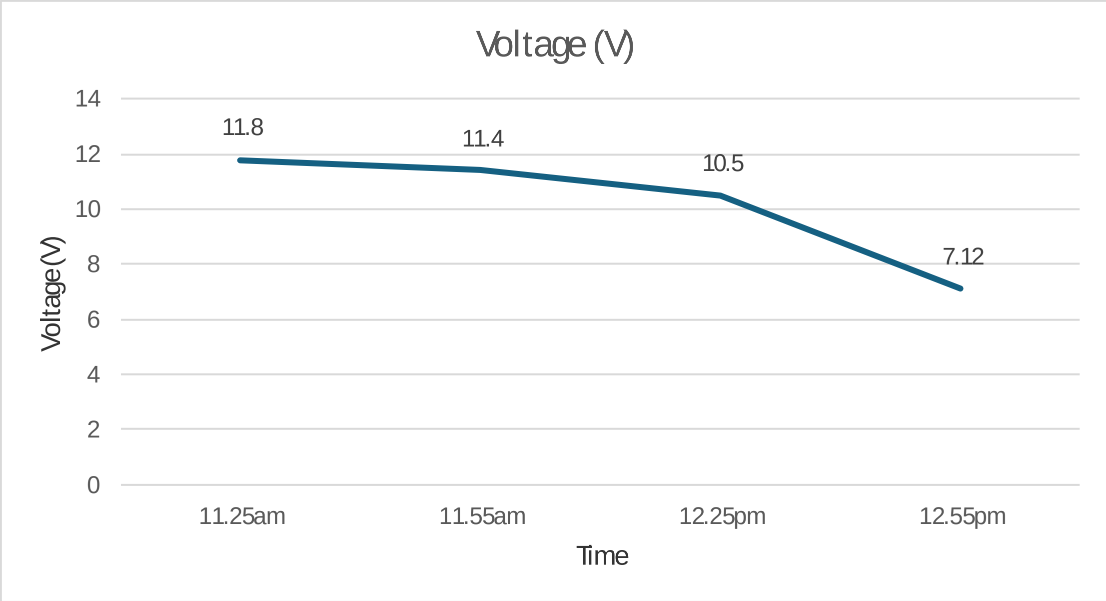

Fig. 16 Voltage vs Time of battery discharge characteristics under DC water pump load

The voltage of the solar-powered DC water pump system declines continuously from 11.8 V to 7.12 V over the recorded time. This signifies that the system is discharging. The voltage stays very consistent at first, which suggests that there is enough energy to power the pump. But the rapid drop at the end of the observation period reveals that either the solar input has dropped or the battery has run out. This means that the voltage is too low for the pump to work at its best. This signifies that the system is almost at its lowest point of operation

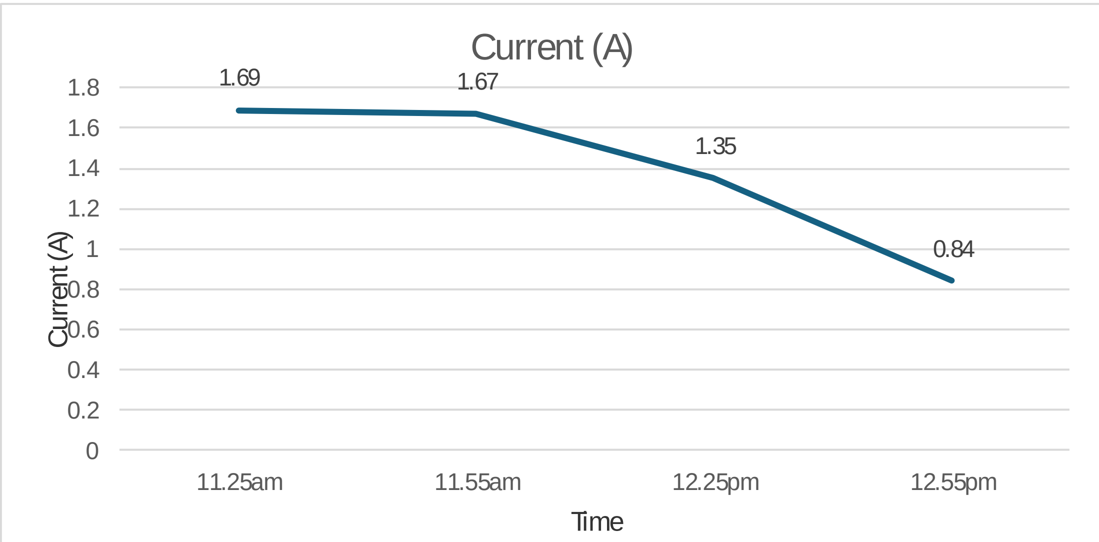

Fig 17 Current vs Time of battery discharge characteristics under DC water pump load

The current going through the DC water pump drops from 1.69 A to 0.84 A over time. This is due to a drop in the system voltage. When the voltage goes up, the pump needs more current to maintain the flow rate and torque up. The pump doesn't perform as well when the voltage dips during discharge since the motor can't draw as much as current. This lowers the mechanical output.

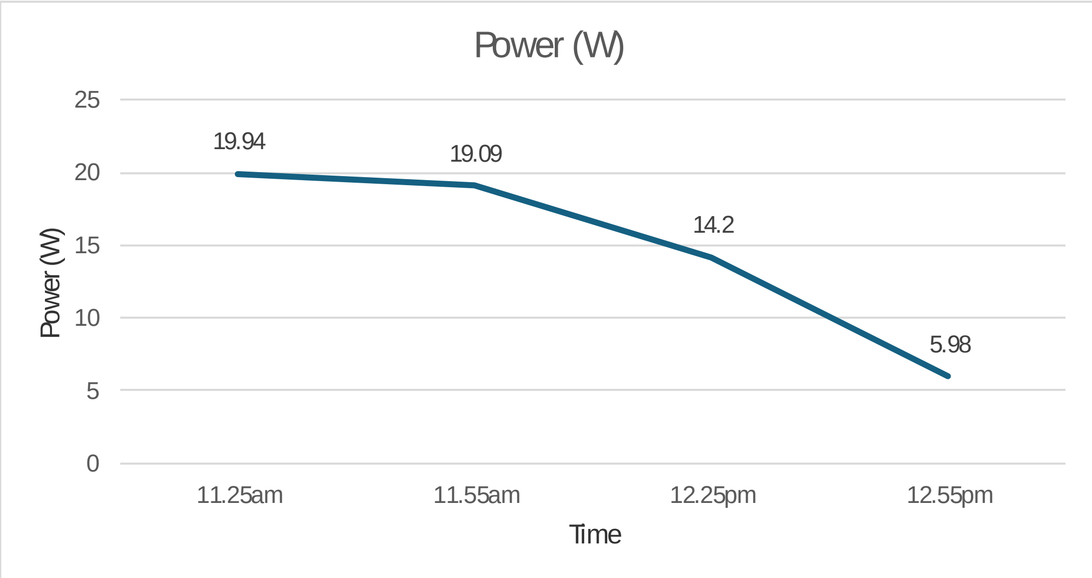

Fig. 18 Power vs Time of battery discharge characteristics under DC water pump load

The power output drops from 19.94 W to 5.98 W, this is because both the voltage and current drop at the same time during discharge this happens because using the DC water pump in the system takes more power. Power is directly related to voltage and current, so the slightly drops trend means that the DC water pump is getting less energy. This drop in power shows that the pump works well only when there is enough solar energy or battery charge, and it gets less effective as the system runs down.

4.3 Comparison DC water pump using electricity grid and solar power

This section presents a comparison of the DC water pump performance when powered by the electricity grid through an AC–DC converter and by the solar/battery system. The operating parameters, including voltage, current, and power, are measured and summarized in Table 5 to evaluate the differences in pump performance under the two power sources. The comparison is carried out to assess the feasibility and effectiveness of using solar energy as an alternative power supply for the DC water pump.

Table 5 Comparison grid and solar power for DC water pump

Parameter	Grid power (AC- DC)	Solar/Battery
Voltage (V)	**12.15**	**11.8**
Current (A)	**1.64**	**1.69**
Power (W)	**19.93**	**19.95**

Table 5 shows the differences in how the DC water pump works when it gets power from the grid (AC–DC conversion) and when it gets power from a solar/battery system. The voltage observed while using grid power was a little higher (12.15 V) than the voltage measured while using solar/battery power (11.8 V). The pump did draw a little more current while it was running on solar/battery power (1.69 A) than when it was running on grid power (1.64 A).

Even though the voltage and current were somewhat different, the DC water pump used almost the same amount of power from both sources: 19.93 W from the grid and 19.95 W from solar/battery power. This means that the pump works at almost the same power level no matter what energy source it uses.

Using solar power to run an aquaponics system shows that is possible to use renewable energy and automated technology together in urban farming. The 50 W solar panel, battery storage, ESP32 microcontroller, and sensor that was chosen to maintain the stable system. Daily energy used in solar power system could power the pumps, sensors, and control units without using to much energy. The sensors for pH, temperature, humidity, and water level all gave consistent and accurate readings and has been recorded. This shows that the IoT-based monitoring system does a great job for making sure that plants and fish are in the good conditions. The automated system reduces the human error during the test. The steady pH levels showed because the peristaltic works well in the system for making sure the fish are in good condition.

Even there is no direct sunlight to the plants, the plants grow well, getting taller and adding more leaves. This means that the aquaponics nutrient cycle was working well, but the plants might grow faster if they were exposed to the sunlight. the fish conditions were checked and showed are still alive actively. This meant that the water quality, oxygen supply, and system stability were good enough for life in the water. The test of charging and discharging the solar battery also showed that the voltage and power levels stayed the same. This means that the system will still work even if the sun changes.

5. Conclusion

This project developed a solar-driven aquaponics model for urban farming that uses less electricity. The method combined aquaculture and hydroponics which is aquaponics system in one system that mostly used solar power which is renewable energy. The system gets the supplies power from the 50 W monocrystalline solar panel, battery storage, and DC-powered parts that worked in stable conditions.

The results showed that the ESP32-based IoT platform works as a monitoring system in the system which is very important to control things like pH, water temperature, humidity, and water level. The study of energy showed that a solar power system could give enough power for everyday use if the battery storage for the system is bigger. The results for plant growth and fish survival showed that the aquaponics system was healthy for living things. The method works well, so it could be a small, long-term, to farm in the cities.

The final product was an aquaponics system that runs on solar power and is good for the environment. It can be monitored and controlled automatically. This project makes urban farming more sustainable by using less water, not using chemical fertilizers, and not relying as much on traditional sources of electricity. In the future, the system could be improved by adding more lights for the plants, making the battery bigger, and making the system bigger so it can be used for more things.

5.1 Recommendation

The finding for solar-powered aquaponics system to work better and reliable. The plants can grow better if you add another lighting system, like solar-powered LED grow lights that use less power. This would make sure there is enough light even when the sun isn't shining very much or when the plants are growing inside. This would help them grow faster and give you more food.

Second, you can improve your renewable energy storage system by adding more batteries or by combining a lithium-based battery with one that lasts longer and works better. With this update, the system would work for longer periods of time, even when it's cloudy or at night. This would make it more reliable overall. Using a maximum power point tracking (MPPT) charge controller will also help you get the most solar energy and speed up the charging process.

Third, the system might need more sensor such as water quality sensors in the future for example to check for ammonia, dissolved oxygen, and nitrates. These numbers are very important for the fish's health and the balance of nutrients. If you could see them in real time, the system would be more automatic and work better. You can also use cloud-based monitoring and powerful data analytics to find patterns over time and improve the system.

Lastly, the system can handle bigger urban farming projects by making the grow bed bigger, adding more fish adding the big fish tank, or adding more solar panels. These changes will make the solar-driven aquaponics system could become a completely green, self-sufficient, and cost-effective way to farm in cities.

Acknowledgement

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