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# SMART FARMING USING A SOLAR-POWERED AQUAPONICS SYSTEM FOR SUSTAINABLE FOOD PRODUCTION

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**Abstract:** This paper discusses the prospect of using solar energy for aquaponics operations. Aquaponic is a platform for farmers to grow fish and plants in the same unit simultaneously. The system is considered a sustainable and green technology. Aquaponics operation may be hampered by the necessity for pumps for continuous water recirculation and air supply within the system, especially if the unit is located far from any power outlet. Given that Malaysia is positioned at the equator and receives an average of 9 hours of sunlight per day throughout the year, with solar intensity as high as 1800–1900 kWh/m2, it is unquestionably a practical solution. This paper examines utilities of aquaponics platforms that can be supported by solar energy and describes equipment for setting up a suitable solar PV system for aquaponics operation. Possible integration of the Internet-of-Things (IoT) for remote monitoring of such solar-operated aquaponics units is also discussed. Analysis revealed that the production and growth rates of the crop and fish grown in the system were unchanged even when fully supplied with energy for 12 hours. The finding indicates the potential for using solar energy as alternative energy for the operation of the aquaponics unit. Aquaponic system particularly benefits farming activities in rural locations without electricity. Despite the high installation costs (a 100 W PV system might cost nearly RM 600), the technology offers long-term savings on electricity expenses and national grid installation fees. In conclusion, the project provided the idea of smart farming using aquaponics for the sustainable production of crops and fish utilizing clean, renewable solar energy.

***Keywords:*** *Aquaponics; Smart farming; sustainability; solar powered system; IoT*

## 1. Aquaponics as a Sustainable Platform for Food Production

Nowadays, vegetables and essential herbs are conventionally cultivated using soil as growing media. However, this conventional cultivation technique is labor-intensive and has long been associated with high operating costs and inconsistent yield caused by adverse and unpredictable weather conditions. Conventional cultivation also requires massive resources such as water, fertilizers, and labor during crop harvesting and post-harvesting periods. The situation is experienced in most developing countries where high-technology agriculture systems are uncommon.

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Aquaponics involves growing aquatic life and plants in a closed system under controlled environments (Maucieri et al., 2018). An example of an aquaponics setup is shown in Figure 1. The Aquaponics technique will give a new perspective on plant cultivation that differs from conventional farming in many ways. Aquaponics cultivation systems rely on the symbiotic balance of ecosystems between the aquatic species and hydroponics products, including vegetables and essential herbs (Hu et al., 2015; Tyson et al., 2011). Due to the absence of synthetic fertilizers used in the cultivation process, the products are considered organics. This technique significantly reduces operating costs, aquatic life waste products (e.g., feces, etc.), and chemical fertilizers usage. In an aquaponics system, waste products from aquatic life are transformed into nutrients that plants need, and plants return clean water to aquatic life. Because the system is recirculating the nutrient-rich water, there is minimal water consumption (Moriarty, 1997). In greenhouses or net houses, cultivation is possible throughout the year to protect plants from insects and the negative impacts of climate change. Aquaponic systems could also boost production yield per square area as the growing space could be constructed vertically or in a stacked layout. The system uses fewer human resources because it often operates automatically with minimal supervision.

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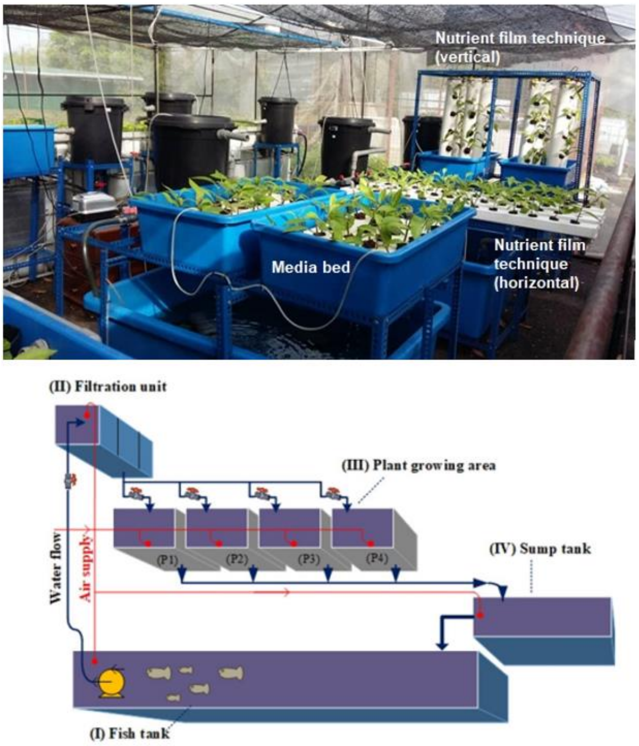


**Figure 1.** Our various backyard-scale aquaponics unit utilizes different types of hydroponic growers (top). Typical schematics of aquaponics operation as established by Zainal Alam et al. (2020) (bottom).

1.1 Main components of an aquaponics system

There are four main components of aquaponics: the aquaculture tank, hydroponics grower, water filtration unit, and water flow system. Materials such as fiber-reinforced polymer, polyethylene, concrete, and canvas can be used to construct aquaculture ponds/tanks. Rounded and sloped bottom tanks are preferable for ease of sludge removal and maintenance. Commercial aquaponic systems typically use aquatic life with rapid growth rates, such as tilapia, to maximize profits. The most popular hydroponic growers for aquaponics operations include media-filled (grow bed) growers, floating raft or deep water cultures (DWC), nutrient film techniques (NFT), and vertical growers. Each grower is distinctive and has their benefits and preferred plants to grow. The media-filled grower system is considered the simplest hydroponics system. One only needs to fill in an empty compartment or tank designated for culturing the plants with adequate substrates for plant growth to use the system without a water filtration unit. Light-expanded clay aggregate (LECA) and gravel larva rock are the typically used substrates for this grower. Both materials are porous and have a large surface area, so they could act as a nitrification and mineralization filter system and allow plant roots to develop within. Alternatively, one could opt for cheap waste substrates such as carbonized rice husk, cocopeat, and a mixture of cocopeat and carbonized rice husk. These alternative media are abundant and easy to purchase locally (Asian countries), ~80% cheaper than common media such as LECA. However, these alternative media require specific installation due to their low surface area and poor biofiltration capacity. The facility typically includes pierced polybags to prevent clogging and a water filtration unit supporting microbial activities in media with low specific surface area (area/volume). The study by Zainal Alam et al. (2020) reported detailed information on these alternative media. In addition, the grow bed system uses components such as a bell siphon that can drain nutrient-rich water effectively, thus compatible with flood and drain mechanisms (reciprocating flow). Consequently, waterlogging at the plant roots is prevented. Therefore, this type of grower is suitable for cultivating many plants, including leafy veggies, herbs, and woody plants such as chilies, eggplants, tomatoes, etc.

The NFT and vertical grower are hydroponics techniques that use horizontal and vertical pipes, respectively, with a thin stream of water from an aquaponics system rich in nutrients. In the NFT system, plants are positioned in holes (with net pots) at the top of the pipes or at the sides of the pipes in the vertical grower, where they can use a thin film of nutrient-rich water. These techniques have very low evaporation because the water is completely shielded from the sun. In addition, the vertical arrangement of the planting area optimizes space usage. However, both growers should have a dedicated water filtration system. Therefore, a mechanical filter must be specifically built to capture suspended materials, followed by a biological filter to facilitate nitrification.

Research has shown that the DWC grower is preferable for large-scale cultivation of a single crop, particularly leafy vegetables, including lettuce, salad leaves, and basil. The DWC technique involves suspending plants on polystyrene sheets, with their roots dipped into the water. However, this technique is unsuitable for growing tall, woody plants such as tomatoes and chilies (Valdez, 2017). In the DWC system, high water flow rates and turbulence would promote plant growth by distributing more necessary ions evenly throughout the roots of the plants. On the contrary, if slower water conditions were applied, it would create stagnant water conditions, which would only negatively impact plant growth due to the low mixing of ions and minerals. Aeration is important in the DWC system, especially in a densely planted canal. Thus, the oxygen demand for plants can cause dissolved oxygen levels to plummet below the minimum level (3 mg/L) (Maucieri et al., 2018). Several small air stones must be placed in the canals to overcome the problem. Similar to NFT and vertical growers, this technique required a dedicated water filtration unit to be installed between the aquatic tank and grower. A few researchers have reviewed comparison studies of these hydroponics systems. For instance, high yield has been reportedly obtained from growing leafy vegetables, such as lettuce (Latuca sativa), in


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bed aquaponics system (Lennard and Leonard, 2006; Shete et al., 2016). According to a specific study on the cultivation of herbs like Gynura procumbens, the DWC approach with adequate aeration (dissolved oxygen) gave the maximum yield and growth rate for the Gynura because it allowed efficient nutrient absorption. (Zainal Alam et al., 2019).

### 1.2 Water filtration unit

Although the choice of hydroponic grower affects the plant growth rate and harvesting yield, the water filtration unit plays a crucial part in the aquaponics system performance as it serves as the heart of the system. The filters complete the nitrogen cycle by providing nutrients rich water to the plants in the hydroponics grower and clean water to the aquatic life in the aquaculture tank. Commonly used water filtration units combine mechanical filters and biofilters arranged in sequence, with the former coming first, followed by the latter. Solid fish wastes like feces and uneaten fish food are removed from fish tanks using mechanical filters, including sedimentation tanks, radial and axial flow clarifiers, sand/bead filters, and baffle filters (Bandi et al., 2016). However, because most fish waste is dissolved in the water as ammonia, it cannot generally be removed using the mechanical filter as the particle size is too small (Somerville et al., 2014). Therefore, the biofilter is required to process this microscopic waste. The bio-filter is designed to have a large surface area supplied with oxygenated water to house most nitrifying bacteria and installed between the mechanical filter and the hydroponic grower. The ammonia-oxidizing bacteria (AOB), such as Nitrosomonas sp., and nitrite-oxidizing bacteria (NOB), such as Nitrobacter sp., convert the ammonia into nitrites and nitrite into nitrates, respectively (Blidariu & Grozea, 2011). Since ammonia and nitrite are toxic to aquatic life, even at low concentrations, the installation of biofiltration is essential. Biofiltration also offers the capacity to boost the conversion of these toxic compounds into nitrates which is needed for plant growth (Bandi et al., 2016). Colonies of nitrifying bacteria can be extensively developed using commercial biofiltration materials with a high specific surface area (SSA). Bio-balls and bio-rings are the commonly used biofiltration media, which are specially shaped plastic or ceramics with huge SSA in the range of 500-700 m2/m3. Natural media such as volcanic tuff and LECA with an SSA of ~300 m2/m3 enables the growth of bacteria. The size (volume) of a biofilter is greater than that of commercial media since it has a lower SSA. Our recent study (Kamarudin et al., 2019) found that axial flow and bio-filter (using bio-balls and bio-rings) combined in a small vessel (single compartment) were sufficient and comparable with using both filters separately in sequence. The systems provide high-quality and nutrient water for healthily growing the red Nile tilapia and herbs, respectively. This compact filtration unit is an innovation by the authors that can reduce the area required to place the filter.

### 1.3 Water flow of aquaponics system

A pump and piping system is necessary for the aquaponics system, and there are important parts of the water flow system. The time for minerals or ions residing in each compartment of the aquaponics platform is closely related to the water flow within the aquaponics system. This factor directly affects the cultivation of the fish and the yield of the plants (Rakocy, 2007). Additionally, the water flow system affects energy consumption and running costs, particularly the pump. Submersible, airlifts, and momentum pumps, such as axial flow and centrifugal pumps, are three commonly used methods of transporting water through an aquaponics system. Submersible pumps are typically employed in various-sized aquaponics setups. Instead of using a water pump, airlift-based aquaponics operations employ air pumps such as air compressors and blowers. Bubbles for oxygenation and mixing are created by pumping air to the bottom of a pipe within the fish tank. The bubbles carry and/or push the water upwards through the column as it heads toward the surface of the water. Airlifts work best at water depths larger than 1 m and generate power in deeper tanks. Airlifts do not clog compared to submersible pumps, and water oxygenation is established through the vertical movement operated by the air bubbles. Air pumps generally have a longer life span than submersible pumps. Moreover, airlifts are more economical as a single air pump, which can be purchased for water circulation and aeration, reducing the capital investment in a second pump. According to Wayua (2015), momentum pumps such as axial flow pumps are used on larger scale systems because they have better pumping efficiencies than air pumps under low lift conditions, which are lesser than 3 m. These pumps are robust and highly resistant to clogging. Since the propeller is submerged in a recirculating aquaponics setup, pumping can start without priming, although axial pumps are more expensive than air pumps.

## 2. Main Utilities for Aquaponics Operation

Water heaters, air blowers, box fans, a pump, and lights for seedling germination in four-season nations are the main electrical components that must be powered by electricity in aquaponics systems (Love et al., 2015). On the contrary, less electrical equipment would be required if the aquaponics systems were set up in tropical regions like Malaysia. Electricity is mainly used for air supply and water circulation. Table 1 compares the electrical equipment and energy use in aquaponics systems built in four-season and tropical countries. In a typical aquaponics system, the water is continuously circulated for 24 hours a day, prompting the need for efficient power consumption. Due to friction, the pumping power is decreased along the pipelines (major losses) and possibly to a smaller extent at each pipe fitting. Additionally, as the water is pushed through the pipe connections, the total water flow rate is projected to decrease by up to 5% (Somerville et al., 2014). Therefore, it


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is recommended to install pipelines with the optimal diameter and use fewer connectors to link the pump, fish tanks, and hydroponic plants to reduce energy consumption. Moreover, alternative power sources such as solar energy or a hybrid of photovoltaic and online grid electrical energy combined with a reciprocating water flow system (alternating on-off mode pump operation) may be a sustainable approach to meeting energy demand in a modern aquaponics system.

**Table 1.** Comparison of common mechanical equipment and energy use in aquaponics systems for four-season and tropical countries

| Equipment | Energy source | Use | Region |
|---|---|---|---|
| Water pump | Electricity | Continuous | Four-season & tropical |
| Air blower | Electricity | Continuous | Four-season & tropical |
| Inflation blower | Electricity | Continuous | Four-season & tropical |
| Box fan | Electricity | Continuous | Four-season & tropical |
| Fluorescent light | Electricity | On-demand | Four-season only |
| Electrical water heaters | Electricity | On-demand | Four-season only |
| Greenhouse fan | Electricity | On-demand | Four-season only |
| Wall-mounted heater | Propane | On-demand | Four-season only |
| Generator | Propane | On-demand | Four-season & tropical |

## 3. Solar Energy: What and How?

Nowadays, solar power is the most eco-friendly and reliable form of renewable energy available for consumers. Solar photovoltaic is one of the most used solar technologies because it converts sunlight directly to electricity. Solar panels are made up of a smaller unit of a solar cell. Photovoltaic cells absorb solar energy during the day. It is composed of n-type and p-type silicon with a depletion layer in the middle. When the sunlight reaches the semiconductor surface, the photons of the light rays absorbed by the semiconductor excite the electrons from atoms, generating electricity. These advantages make solar PV a suitable energy source for the aquaponics system.

### 3.1 Types of solar PV systems

The solar cell matrix is a crucial component in any solar PV system, which functions mainly to convert energy from light into electricity. Depending on the types of raw materials used, solar PV can be classified into three different types. These include single-crystal silicon solar cells, polycrystalline silicon solar cells, and amorphous silicon solar cells.

#### 3.1.1 Monocrystalline silicon (single silicon)

The amount of silicon in the materials used for building solar panels directly influences system efficiency. Efficiency in energy generation improved with an increasing amount of silicon. A single silicon solar panel is currently widely used in numerous settings. Figure 2 briefly shows the construction of solar panels from the combination of monocrystalline solar cells. A single silicon-based solar panel can receive the same quantity of sunlight and thus, absorbs more energy than other solar panels and produce more electricity (i.e., current and/or DC voltage energy). Despite the benefits, silicon-based solar panels have a high per-panel cost, which becomes its major drawback (Eldin et al., 2015).

**Figure 2.** Combination of the monocrystalline cells to form a single silicon solar panel (Eldin et al., 2015).

#### 3.1.2 Polycrystalline silicon (multi-silicon)

A polycrystalline solar panel is typically made of polycrystalline silicon solar cells. Energy demands for different applications can be met based on the arrangement of the PV modules. Depending on the intended application, PV modules are also available at different power wattages that can generate electricity at varying levels, i.e., from 40W up to 1kW. The two most popular options on the market are thin film solar cells and crystalline silicon solar cell films, each of which has advantages and disadvantages. Manufacturing costs for the crystalline silicon solar cell film may be comparably low, but silicon consumption is high, leading to high photoelectric conversion efficiency. When it comes to thin-film solar cells, the majority of them are used to provide electricity for outdoor power generation. However, the cost of the equipment is high for the system to generate high power efficiently (Sagar et al., 2018). Figure 3 depicts a solar panel that combines polycrystalline units into a multi-silicon panel.



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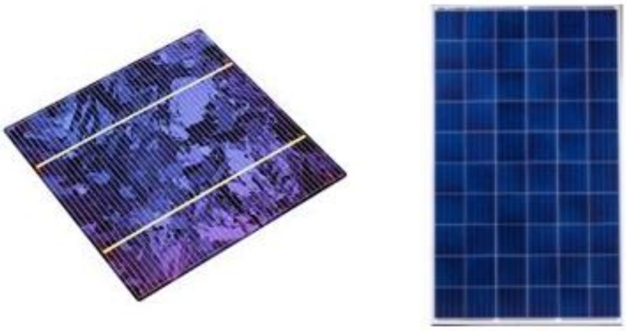

**Figure 3.** Combination of polycrystalline into a multi-silicon solar panel (Eldin et al., 2015).

3.1.3 Amorphous silicon solar panel

As shown in Figure 4, amorphous silicon solar cells are the new generation of thin-film solar cells. The production method is slightly different from monocrystalline and polycrystalline silicon solar cells and has been greatly simplified. This panel requires less silicon, hence the low electricity generated. The primary advantages of the panel include its ability to generate electricity under low light conditions. However, the conversion efficiency is poor due to the amorphous silicon solar cell and declines with time (Chandel et al., 2015).

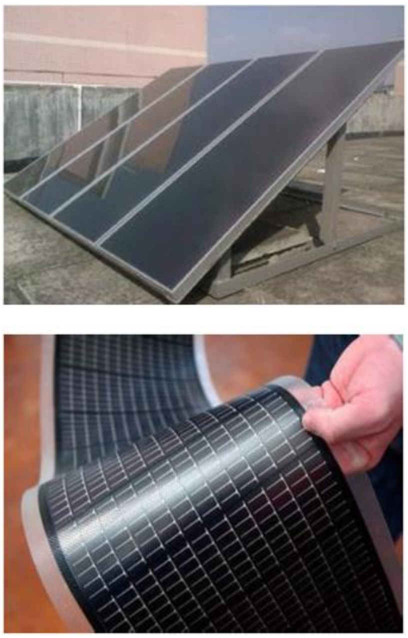

**Figure 4.** Amorphous silicon and flexible solar cells (Chandel et al., 2015).

3.2 Type of energy from solar cells

The two forms of electric current are alternating current (AC) and direct current (DC). Solar panels typically produce direct current (DC). The electrons generated from the sunlight flow in the same direction, generating a direct current. The mechanism is similar to batteries with positive and negative terminus and the current flowing in the same direction between the two points. On the contrary, the electrical grid and power supplied to most residential households are in the form of AC. Similarly, most plug-in submersible water pumps used in aquaponics systems are powered by AC. Inverters are required to convert DC into AC to support the functioning of water pumps. DC-coupled batteries are usually used to store the power received directly from the solar panels. A multi-purpose controller is often used to manage energy from solar panels efficiently. The primary function of the controller is to channel the energy received from the solar PV panel to batteries for energy storage and to the electrical appliances in the form of DC or AC. Notably, converting solar PV energy from DC to AC may result in a voltage drop in the system, lowering system efficiency. For this reason, a DC-powered water pump may be opted for if the aquaponic system were to be powered by solar energy.

## 4. Feasibility of Solar-Operated Aquaponic Platform

The prospect of electricity generation from solar energy in Malaysia is up-and-coming. Malaysia is strategically located near the equator, and its climate is hot and humid all year round (Ahmad et al., 2013). Malaysia receives an average of six hours of sunshine per day, with up to nine hours on some days in January, and local temperatures between 26 °C to 32 °C annually, despite the occasional heavy rainfall (Shafie et al., 2011). Solar energy is abundant in Malaysia, with records showing a yearly average solar intensity between 1500 kWh/m2 and 1900 kWh/m2, which is among the highest in the world (Ahmad et al., 2013; Shafie et al., 2011; Mohamad et al., 2013). The solar intensity distributions across the Peninsula and the Borneo Islands of Malaysia are shown in Figure 5. Based on the data from Ahmad et al. (2013), the Northern states of Malaysia and the northwest coast of Sabah have recorded the highest solar intensity, higher than 1750 kWh/m2. The central region and part of the southern region of Malaysia could also be potential sites for solar energy generation, with a solar intensity in the range of 1600-1700 kWh/m2.



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**Figure 5.** Solar intensity distribution in Malaysia, redrawn based on solar intensity contour map retrieved from Ahmad et al. (2013).

Given its reputation as a clean, renewable energy source, the Malaysian government has started to provide attractive incentives to companies producing solar energy. The Feed-in-Tariff (FIT) program is part of a new policy that pays everyone for the renewable energy they create whether they connect it to the national grid or use it for personal use (Shukla et al., 2017). This program has inspired many stakeholders, including locals, business owners, and farmers, to install solar PV systems on their premises. Attractive new policies and/or incentives by the government and the long-term benefits of solar energy should become the driving force for incorporating solar energy into aquaponics systems.

However, integrating solar power into the aquaponics platform is not straightforward. Various design factors must be considered. The factors include the number of PV arrays and capacity (i.e., power generation in watts per square meter, W/m2) of each PV module. The PV must be carefully selected to meet the power required for aquaponic operation, where energy is mainly used for water aeration and circulation in numerous tanks. It is generally recommended to oversize the power wattage of a solar panel by approximately 30% higher than the wattage rating of the pump to account for the less ideal weather conditions (Kyi et al., 2016). The battery capacity must also be considered for a prolonged pump operation. Solar panels with a size larger than the battery bank are typically employed for voltage generation to address concerns with voltage drop and power fluctuation or to make up for any energy loss due to wear and tear (Kyi et al., 2016; Pradhan et al., 2012). Another crucial element is how the solar panels are installed and positioned. Since Malaysia is located within tropical latitudes, mounting the panels onto a rigid structure is more economical than an adjustable panel with sun-tracking features. This is because the sun does not change its angle much at this latitude, and installing a panel that tracks the sun as it moves across the sky is expensive. (Ahmad et al., 2013). A more logical choice would be to add more solar panels. Positioning the panels can be challenging but for a start, the panels can be placed to face a full sun without any shade. Each design element is interconnected with the others and significantly impacts energy generation.

Figure 6 shows the comparison of the power output from two different solar panels on a sunny day (Ahmad et al., 2013; Mohamad et al., 2013). The figure shows that the maximum average power output is achievable during the high noon period, i.e., between 12.00 p.m. and 3.00 p.m. Moreover, battery banks linked to the solar panels are expected to be fully charged during these hours. Beyond this time, it is assumed that less energy was generated and that pumps will likely operate less efficiently. The data highlights that a solar-powered system/pump is weather-dependent. Although solar energy can still be generated during cloudy and rainy days, the efficiency of the solar panels will decline, making the pump less efficient. Similarly, the pump operation is expected to last only a few hours after sunset.


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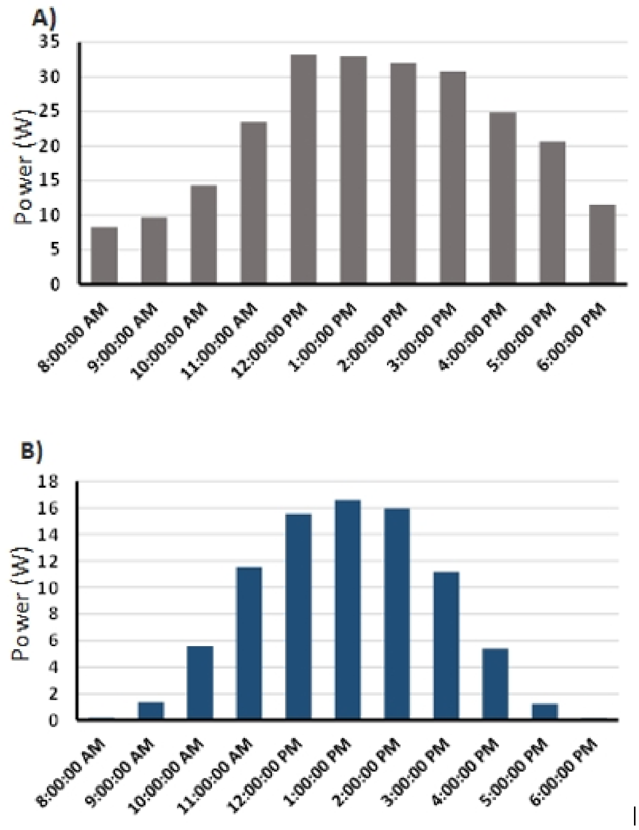


**Figure 6.** Average output power (W) of the solar module on a sunny day based on data from (a) Mohamad et al. (2013) and (b) Ahmad et al. (2013).

A brief investigation was carried out to evaluate the conditions of the crops and the water quality in an aquaponics setup equipped with water pumps that only operated during the day for 12 hours and were turned off throughout the night. The study was performed to simulate a scenario that resembles the operation of a solar-powered aquaponics system where a whole-day pump operation may not be sustainable. Plants were grown utilizing a floating raft grower for the trial duration, which lasted 12 weeks. Our findings reveal that the ammonia level in the fish tank remained reasonably low, i.e., about 0.22 mg/L, below the critical level of 1 mg/L for the survival of aquatic life. The dissolved oxygen level was also maintained within the range of 6 to 7.2 mg/L, with the mean water pH measured at approximately 6.68 ± 0.05. Notably, no fish death was recorded, and the growth of both plants and fish was reportedly steady. The plants were growing steadily despite the slight nutritional deficit, probably due to the lack of water circulation.

The research showed that the aquaponics system could continue to run properly even if the pump was turned off for 24 hours. This finding suggests that a solar-powered aquaponics platform is feasible and that crop yield would be comparable to crops grown with constant pumping. A vertical nutrition film technique (NFT) grower is deemed an inappropriate choice considering the absence of water flowing in the system when the pump is turned off, creating osmotic stress in the plants. As a result, plant growth is halted, and plant leaves begin to collapse because of a lack of nutrients and a significant reduction in respiration and photosynthesis activities (Delaide et al., 2017; Bittsanszky et al., 2016). While solar energy may have seemed like a viable alternative, a high installation cost compared to a monthly electricity bill may hamper its usefulness and could negatively impact the sustainability of the entire aquaponics operation. The cost of installing a PV system that comprises the pump, solar panel, 100 Ah battery, AC-DC converter, solar charge controller, and the associated electronics wiring and components might reach RM 1450 for a 40-W AC pump operation that runs continuously throughout the year. Suppose one decided to use the solar-operated pump, i.e., installation of a PV system for domestic use. In that case, the payback period is about eight years (i.e., based on electricity bill rates of about RM 0.50 per kWh). Alternatively, suppose one decided to sell the electricity generated back to the main grid. In that case, a shorter payback period can be achieved, i.e., around five years of revenues based on a Feed-in Tariff of RM 1.13 per kWh (rates designated for electricity generation by solar introduced by the government of Malaysia). A comparison of both scenarios is presented in Figure 7. Ideally, a solar PV system is considered a cost-effective option that reduces monthly electricity bills. Installing a solar-powered aquaponic system may be feasible in a rural area with no electricity. With the advantage of a simpler setup, solar energy generation performs comparably with a biological approach using bacteria for generating electricity (Makhtar and Tajarudin, 2020).

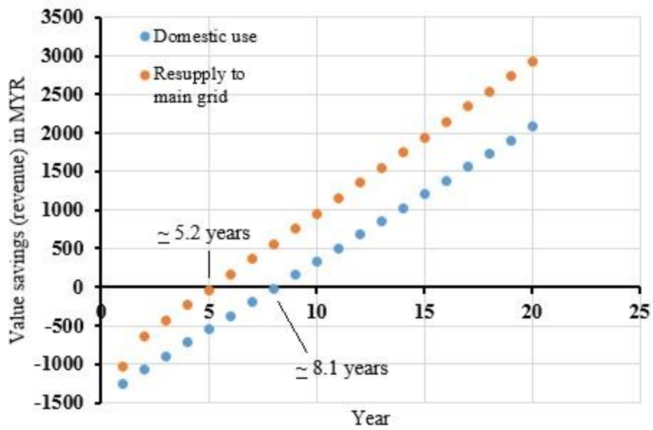


**Figure 7.** The estimated payback period based on the production of solar energy for domestic use and the resupply of power to the main grid for the daily operation of a 40-W pump.


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## 5. Management of Solar Energy Via Internet-of-Things (IoT)

Real-time monitoring of the various parameters and functions of the photovoltaic system component using the IoT is crucial for managing solar-powered aquaponics systems. IoT can be employed to improve energy use efficiency, increase the share of renewable energy, and reduce the associated environmental impacts (Motlagh et al., 2020).

The Aquaponics platform setup requires a constant and clean electric energy supply to power the various pumps for water circulation, aeration for oxygen distribution, sensors, and other devices needed for the survival of aquatic life. IoT involves the interconnection and communication of devices through the internet using wireless standards, such as Wi-Fi, Lora, and Sigfox, for efficient data transmission (Elihaj et al., 2018; Emmanuel et al., 2020). This technology could be adapted to monitor solar-related parameters and devices to ensure optimal system performance. Figure 9 illustrates the framework of interconnected devices for monitoring photovoltaic energy systems via IoT. The framework consists of the photo voltaic energy system, the wireless gateway, and the visualization (Kumar et al., 2018).

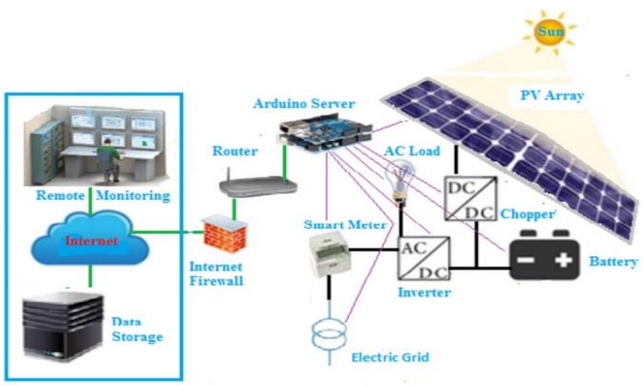


**Figure 8.** IoT-based architecture for the management of photovoltaic energy systems (Kumar et al., 2018)

Sensors are vital components of IoT used in a solar-powered aquaponics system, allowing real-time weather monitoring that affects solar radiation and the light incident on photovoltaic cells. IoT-based sensors may measure the variables such as air temperature, rainfall, air humidity, wind, UV index, and value. One of its most important components is the light-dependent resistor (LDR), whose resistance changes depending on the amount of light that hits it. The value and intensity of these variables help maintain the solar panel, such as the direction of placement, tilt angle, etc. The collection of dust on the solar panel can also be detected using an LDR, camera, and any IoT-based processing board with a suitable inbuilt algorithm and calibration (Babu et al., 2018; Lee and Park, 2019). This approach can help optimize the energy efficiency of solar panels for effective storage of battery charges in the system.

To monitor power consumption, solar energy devices, including photovoltaic cells, deep-cycle batteries, DC-to-DC converters (choppers), and AC-to-DC inverters can be wirelessly interfaced with Arduino or Raspberry Pi prototyping boards and coupled with current and voltage monitoring sensors (Sathiya et al., 2018; Phung et al., 2017). Monitoring parameters will let users know the performance and status of the system. Additionally, the gateway acts as a conduit for information transfer via the network between energy devices and the internet-based visualization for real-time monitoring. When using an IoT dashboard like ThingSpeak or another website platform or mobile app, the data collected may be utilized to assess the system's effectiveness based on factors like energy usage, weather, and other factors (Rahman et al., 2019). IoT makes sharing information between the farm operator and the management possible.

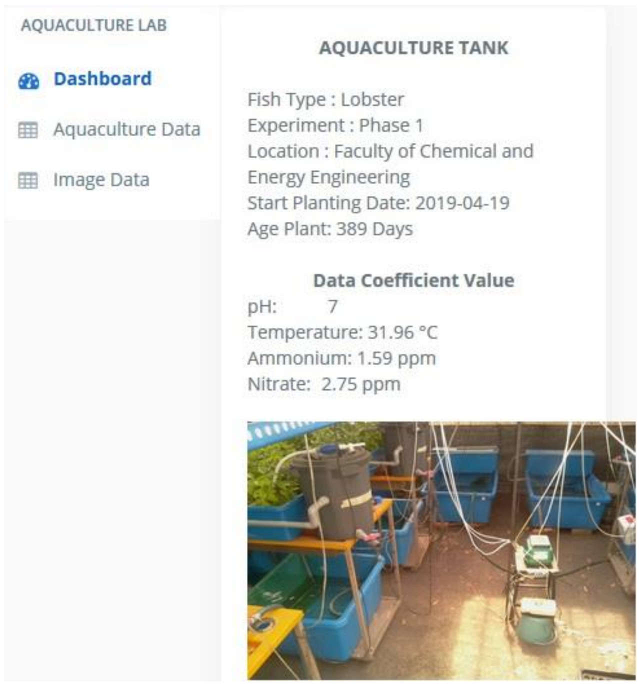


**Figure 9.** One of our IoT-based monitoring systems for measuring water quality in aquaponics systems (www.agritech.com).

Integrating IoT into the management of solar energy for aquaponics system can help reduce the number of visits to aquaponics farms since all the monitored parameters can be remotely viewed via phone or computer, as shown in Figure 8. Users will also be able to recognize uncommon faults on each parameter related to photovoltaic equipment, allowing them to control them remotely or go to the location for repair. Therefore, IoT-based solar energy management can help enhance the monitoring and tracking control of the system to ensure an efficient aquaponics system.


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## 6. Concluding Remarks

Aquaponics has emerged as an increasingly popular food production method worldwide. It brings forth the smart farming concept, combining aquaculture with hydroponic farming. In aquaponics, nutrient-rich water houses aquatic life, such as fish, and provides fertilizers for plants. The plants return the clean water to the system by taking up the nutrient. The technology consumes less water than the conventional soil-based plant-growing system since the water is circulated through the plant growers. Aquaponics also generate relatively little waste and are soil-less. The system can also be installed at various scales, from as small as ~1 m2 indoor or backyard growing to a large-scale pond system. Most importantly, the system can generate two agricultural products (fish and vegetables) from a single nitrogen cycle source and is considered sustainable. However, the need for electricity to run pumps (for water recirculation and aeration) can be a problem if the aquaponics is set up far away from any power outlets. Analysis revealed that it is possible to run an aquaponics system powered by a solar PV system, in which the pumps function by harnessing the energy from the solar panels. Solar energy has been proven a viable alternative for long-term benefits despite the high installation cost. The power can be generated continuously for at least nine hours daily with a solar intensity of around 1800–1900 kWh/m2. IoT integration uses little energy, is helpful for remote process monitoring, and reduces the labor required for the operation.

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