Internet of Things and Cyber-Physical Systems 2 (2022) 212–225

Contents lists available at ScienceDirect

Internet of Things and Cyber-Physical Systems

journal homepage: www.keaipublishing.com/en/journals/internet-of-things-and-cyber-physical-systems

Design and implementation of solar-powered with IoT-Enabled portable irrigation system

Roshahliza M. Ramli [a,*], Waheb A. Jabbar [b]

[a] Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang, 26600, Pekan, Pahang, Malaysia
[b] School of Engineering and the Built Environment, Birmingham City University, Birmingham, B4 7XG, UK

ARTICLE INFO

Keywords:
Blynk
IoT
NodeMCU
Smart irrigation
Solar energy
Water pump

ABSTRACT

This paper proposes a solar-powered portable water pump (SPWP) for IoT-enabled smart irrigation system (IoT-SIS). A NodeMCU microcontroller with a Wi-Fi interface and soil moisture, temperature, and humidity sensors are exploited to monitor and control the water pump and build an IoT-based irrigation system. The proposed irrigation system updates the gathered information from sensors (moisture, temperature, and humidity) using an integrated algorithm to the Blynk IoT cloud in real-time. Farmers can access this information and control the water pump accordingly via a user-friendly interface using their smartphones. The portable and eco-friendly water pump is powered via a solar panel and can be controlled using Blynk mobile application, which is also used to monitor the surroundings. The fabricated pump is inspired by wheeled travel luggage and is equipped with a water filter and multi-nozzles sprayer. The developed solar-based water pump has managed to save electricity and mitigate operational costs. Furthermore, the integration of the IoT concept has facilitated real-time monitoring and control of the pump; thus, enhancing the water usage efficiency and enabling convenient farming operations. The system functionality has been practically tested in a real environment, and its performance has been evaluated.

1. Introduction

Water pumping is tremendously utilized in irrigation systems by many farmers worldwide. Irrigation technologies change rapidly from traditional irrigation activities that mainly depend on farmers to modern farm machinery that utilizes various machines and systems for water pumping and plantation process [1]. The water pump is primarily used for irrigation and livestock watering. Irrigation is a wide field focusing on water supply for growing plants and maintaining landscaping features, including trees, shrubs, grass, and flowers [2–4]. Water pumping is the key player in irrigation systems to supply the required water capacity at a specific area with adequate pressure and flow rate [5]. In conventional irrigation systems, farmers mainly depend on either diesel/fossil fuel-based pumps or electric-based pumps. However, fossil fuel and diesel-based water pumps are not environmental-friendly since they cause air pollution and contribute to climate change which is one of the serious problems in our world [6–8]. This is because the combustion of the diesel and fossil fuel release carbon dioxide which contributes in generating greenhouse effect and global warming and cause a risk toward human [9]. Also, the demand for electricity keeps increasing due to the faster development of agriculture in rural areas [10]. In other words, electricity deficit, fuel cost, air pollution, water wastage, and lack of new technologies utilization in agriculture pose significant concerns in conventional irrigation systems. Therefore, there is a real need for utilizing renewable energy resources to supply agricultural activities with the required energy.

Solar energy is among the promising alternatives in irrigation systems that can be applied in agricultural activities to reduce electricity usage and minimize the consumed fossil fuel, especially for farmers in rural areas [11]. It is an affordable choice for future energy compared to other renewable energies because of its availability in abundance, cost-effectiveness, installation cost, and efficiency [12]. Usually, the solar panel is attached to a voltage regulator, inverter, and battery to form a Photovoltaic (PV) System. Hence, the water pump should be equipped with a PV system to build a solar-powered water pump. In addition, in this era of technology, the emerging evolution of the Internet of Things (IoT) and advanced automation and control systems are being leveraged to realize smart irrigation systems with real-time monitoring and automated control. A solar-powered water pump with the Internet of Things (IoT) support is a promising alternative to overcome constraints in

* Corresponding author.
E-mail addresses: roshahliza@ump.edu.my (R.M. Ramli), waheb.abdullah@bcu.ac.uk (W.A. Jabbar).

https://doi.org/10.1016/j.iotcps.2022.12.002
Received 18 August 2022; Received in revised form 3 December 2022; Accepted 19 December 2022
Available online 27 December 2022

conventional irrigation methods.

IoT is a recent paradigm of communication technology, where all objects with communication interfaces, such as sensors, appliances, smartphones, tablets, and laptops, can connect with each other and with the Internet. The main intention of IoT is to form a global and smart world using a global network system; thus, it creates a sense for data collection from a huge number of devices/sensors/nodes worldwide and makes it available over the Internet. IoT applications enhance all areas of our daily lives and become more inspiring and pervasive in many emerging domains, including smart grid, smart city, home automation, environmental monitoring, smart agriculture, healthcare and medical aids, and industrial automation. Consequently, integrating the IoT concept to construct a smart irrigation system will help farmers automate the water pumping operation and improve the farming and plantation process with less effort and cost.

Generally, the greater the solar radiation, the greater the evapotranspiration, the greater the need for irrigation, and the greater the solar energy to supply power for water application. Therefore, in this paper, a solar-powered portable water pump is introduced by integrating a PV system with an electric water pump for irrigation purposes. The IoT concept is enabled to form a smart irrigation system that can update the collected information through sensors to the Internet and can be accessed by farmers using a mobile application via smartphones. A solar-powered water pump is a water pump that uses energy generated by a solar panel, so it is cost-effective and environmental-friendly. The solar water pump can run continuously for most of the daytime, directly from solar cells and during nighttime using a battery. Besides, this solar water pump is portable and free of power lines. It is suited for the farmer where the water resources are in remote locations. The system is equipped with nozzles to control the water flow rate and a filter for purifying the irrigation water. The portable nature of the multi-nozzles of the solar-powered water pump is an add-on feature that is required to cover a wider area and different plant kinds using a single pump; thus, provides more convenience to the farmers. An IoT-based control system is attached to the developed solar-powered water pump to form a smart irrigation system for real-time monitoring and remote control. The smart irrigation system includes a NodeMCU microcontroller, moisture and temperature/humidity sensors, and a relay board.

The main contribution of this study is to design and fabricate a cost-effective solar-powered water pump with IoT integration for the smart irrigation system. To fulfil these requirements, this study adopts the following objectives and contributions:

(i) Design and fabrication of a solar-powered portable water pump (SPWP) to save energy and fuel costs and mitigate air pollution using a renewable energy resource. The portability nature of the SPWP makes it easy to transport and relocate.
(ii) Development of an IoT-based smart irrigation system (IoT-SIS) with an integrated algorithm to monitor the condition of the surroundings and remotely control the pump over the Internet using the Blynk IoT platform and mobile application.
(iii) Implementation of the developed smart irrigation system with the solar-powered water pump (IoT–SIS–SPWP) in a real environment and conducting practical experiments to validate its performance and functionality.

The rest of this paper is organized as follows. The next section presents the literature review and related studies. Section III presents the methods and materials. The system validation and performance testing are explained in Section IV. Finally, the article is concluded in Section V.

2. Literature review

There are numerous areas where the rainwater is not adequate to accomplish this aim, and many of these regions face drought for various periods. Irrigation is the precise technology to cope with these issues based on several factors related to soil and crops [13]. Water pumps are widely used in farming and irrigation systems. The normal water pump is powered by a diesel or fossil fuel engine to rotate. Several issues are rising due to the usage of such water pumps, including fuel price, maintenance cost, air pollution, generated noise, efficiency, and lack of remote control and monitoring [14]. Such water pumps need fuel or diesel as a supplement; thus, the farmer needs to spend extra operation costs for buying these supplements and maintaining the continuous operation of pumps that have a short life expectancy. Such add-on costs can be challenging, especially for the farmers who own their farms on a medium and small scale since their profit is not too much, and they cannot afford this high cost. Furthermore, the carbon dioxide released from fossil fuel and diesel into the atmosphere may also cause acid rain that can corrode the soil, vegetation, and crops [15].

From another perspective, using main grid electricity to feed electric water pumps for farming and irrigation in rural areas is another challenge [16]. The electricity demand is growing rapidly worldwide with the increase in the human population, urbanization, and modernization. About 70% of the population is employed in the agriculture sector, which consumed 18% of the total power generated compared to other sectors [17]. This is required to produce a considerable amount of electricity to support the energy requirements for agriculture field activities to secure irrigation water in all rural areas. Governments have to spend a lot of money and resources to meet the energy demand in agriculture, particularly supplying electrical energy to rural areas, which is not always an easy solution [18].

Recently, more attention is dedicated to current studies on real-time monitoring and advancement in remote control concepts over the Internet for precision irrigation, particularly in rural areas. It is expected that the new IoT paradigm will play a crucial role in the agriculture field to improve the remote control of irrigation systems and attain real-time information about every aspect related to plantation and farming activities. Therefore, smart irrigation systems that utilize various microcontrollers, sensors, actuators, and wireless technologies to send agriculture and irrigation-related data to an IoT platform are necessary. Such an IoT-based irrigation system will help farmers to monitor their farms' conditions over the Internet using their smart devices, in addition to switching ON/OFF the water pumps remotely via a mobile application.

The solar photovoltaic system converts sunlight into electric energy directly through the photovoltaic effect. This solar photovoltaic system is a valuable and sustainable approach to overcoming the current environmental issue and crisis. The smallest element of a PV system is the solar cell. Each solar cell has two or more specially prepared layers of semiconductor material that produce direct current (DC) electricity when exposed to light. The wiring collects this DC in the panel. It is then supplied either to a DC pump, which pumps water whenever the sun shines or stored in batteries for later use by the pump. This kind of green energy can ensure energy, water, and environmental security. The PV system and water pump combination is a necessity, as the solar water pump is used widely in agricultural production. PV system does not produce any harmful by-products, which cause environmental pollution. Since solar energy is not extracted from the earth's layers, so it will not cause any harmful pollutants to the surroundings. The basic working principle of a PV system is that the photovoltaic cell converts the solar energy from sunlight to electrical energy that can be used to feed loads through the controller, which keeps the battery charging during the daytime. The produced energy during the daytime is stored in a battery to be used in the nighttime.

Solar photovoltaic water pumping system is an ideal alternative for electricity, fossil fuel, and diesel-based water pumps. In 1970, a study made to explore the economic feasibility and practicality of solar water pumps brought some effort. The solar water pump is a combination of a solar photovoltaic and pumping system. It involves multidisciplinary areas, including electrical, mechanical, electronics, civil, and computer engineering. In the past few decades, the world still depends on those limited and non-renewable energy sources which take millions of years to replenish. After industrialization, the energy demand increased, and the world is facing many environmental problems like acid rain, global warming, and greenhouse effects. The global surface temperature is 0.6° Celsius higher than the average temperature during 1900–2010 [19].

The main components of a solar water pump consist of a solar panel, pump, electric motor, water distribution nozzles, water filter, and controller. The electric motor used in the water pump is to rotate the pump and manages the AC or DC. Besides, the function of the controller in the water pump is to adjust the motor speed and the output power. The solar water pump is more efficient and economical than the traditional water pump; it is extremely useful for the farmer who works on a small and medium-scale farm. This kind of solar water pump is not only used in the crop; it can also be used in feeding, gardens, and irrigation. The operation concept of the solar water pump is simple, where the solar panel collects the solar energy from the sun and converts it into electrical energy through the silicon wafers embedded in the solar photovoltaic panel. The electric energy is then transferred to a DC-based motor pump system which operates the motor. The motor rotates the shaft, coupled to the mono-block pump, and the pump starts lifting the groundwater. There are two types of water pumps, which are surface water pumps and submersible water pumps. The surface water pump is suitable for lifting and pumping the water from a maximum depth of 20 m, while a submersible water pump can be used in an area of greater depth of 50 m [20].

In [21], the authors proposed a user-friendly, reliable, and automated 3- phase water pump control system based on Wi-Fi to be used by farmers. The system includes monitoring electric supply availability, the water level inside the reservoir, the water flow rate, and water pump short circuit conditions. The NodeMCU ESP8266 is the microcontroller of this system. However, system design is very sensitive and should be handled with utmost care because the microcontroller is a 5 V device. It is employed to control a high-voltage 3-phase irrigation pump.

Ref. [22] focused on multiple factors that influence the PV water pump performance. They claimed that the cell's temperature, PV module degradation, incidence angle, surface dust, and efficiency of the motor pump have the most impact on the system performance. In addition, mismatching, self-shading, and shadowing are other involved factors that affect the performance of solar-powered pumps. In Ref. [23], the authors determined the number of PV modules and the pumping power that is required in PV-based water pumps with a battery bank. A comparison study between conventional pumps and solar-powered pumps was carried out regarding the required cost for installation, operation, maintenance, and total life cycle. The results proved that the PV-based water pumps saved a lot of fuel and engine oil costs, which results in reducing CO_2, air pollution, and noise. The study considered other geographical characteristics, flowrate and optimum tilt angle.

A study in Ref. [24] addressed the simultaneous operation of irrigation areas using standalone solar pumps. Such a system entails the direct application of the pumped water to the different sectors depending on the reservoir; thus, it decreases the total cost and eliminates the evaporation process. The authors developed a model based on linear programming. The model operation is based on the required water volume and the PV power. The result proved that the simultaneous operation of PV-based pumps provided higher efficiency and saved energy compared to the individual operation. In Ref. [25], the authors devoted the study to developing an IoT-based system for solar water pumping, which can be operated and controlled via a vision-based technique using a fuzzy-based algorithm. The system observes the soil moisture, temperature, and humidity and runs the pump accordingly. The system also supports manual and remote control by the user and controls automatically via the Fuzzy-based control mode. Ref. [26] highlighted the design and implementation of a water pumping system based on the health of plants. The system model supports the automatic start/stop of the electric motor based on water threshold values. The study analyzed the sensor data to decide on irrigation time according to plant health status with the plant's threshold value. An emergency notification about plant health will be sent to the farmer via email over the IoT platform when needed. The farmer also can access information regarding to soil and environment parameters including soil pH value and moisture, temperature and flame values through Graphical User Interface (GUI) to decide whether the plants need to be irrigated.

In this regard, PV-based water pumping is among the viable alternatives in irrigation systems that have attracted considerable attention and have been deployed in numerous remote regions. Such solar-powered pumps can be used in various applications to supply water in rural areas ranging from irrigation to livestock. PV-based pumps have many features that make them attractive to be a substitute for conventional water pumping systems. It is based on green and clean energy without carbon dioxide emission (no fossil fuel), eco-friendly, reliable, with no noise, and low cost for operation and maintenance. The reported literature proved that solar-powered water pumps are more economical and can compete in low pumping capacities than conventional fuel-based pumps and wind-powered pumps. Some studies focused on the configuration parameters of the water pumping system, and others studied motors and pump types based on applications. Some addressed controlling water pumping systems, while other studies were devoted to analyzing various economic and environmental parameters. Although many solar-powered water pumping systems are already implemented in many countries, it still limited to small and medium scales and need to be promoted at a large scale. Integration of IoT-control concepts is necessary to convince farmers in remote areas to switch their manual/local control pumps with the remote IoT-based PV water pumping system. Such an IoT system is required to persuade farmers that solar-powered pumps with automation capabilities and real-time monitoring are the correct option to reduce production costs, increase irrigation efficiency, improve plantation quality, and keep plants safe and healthy. Such transformation is necessary for developing nations where agriculture is the main activity, and solar irradiance is sufficient throughout the year.

Overall, many studies instigated solar-powered water pump applications in irrigation systems. However, to the best of our knowledge, limited studies focused on developing IoT-based smart irrigation using solar-powered water pumping systems. In addition, none of the previous studies focused on using a portable PV-based water pump as a standalone system in farming activities. Most of the proposed systems were not validated in a natural environment, even though they were tested in LABs using simulation models or prototypes. Therefore, we developed a portable solar-powered water pump with an IoT-enabled controller as an innovative irrigation system in this study. The NodeMCU ESP8266 microcontroller enables users to send commands towards the pump according to the collected readings from the sensors. A mobile application to monitor the pump and control the system has been created, and it can be used from a certain distance with the use of an internet connection. Thus, it can be accessed anywhere and anytime when the Internet connection is available. This will lessen the burden on the user and increase the efficiency of the water pump. For instance, the farmer can start and stop water pumping through the phone without being close to the water pump. A mobile application is used to remotely control the on-and-off operation of the water pump from smartphones and to monitor the surroundings over the Blynk IoT platform.

3. Methods and materials

This section defines the methods and research activities adopted in this study, including the methodical organization of various research phases in conjunction with the detailed design and implementation of the proposed solar-powered water pump with the IoT-based smart irrigation system. Moreover, the components selection and their integration are explained in detail to fulfil the design objectives. A portable solar-powered pump for the IoT-based irrigation system was fabricated. The hardware development of the IoT-based system was carried out by utilizing the NodeMCU ESP8266 Wi-Fi module as a microcontroller, and sensors were selected to measure the considered parameters. The relay board has been decided to control the switching process of the pump. After that, software was developed by integrating the required sensor libraries using Arduino IDE as the interface between the NodeMCU and the programming device. The arrangement/sequence of the code must be improved according to the thought of the entire water pumping system, whether which sensor runs first and then followed by the next sensor with each action once the sensors are triggered. The Blynk IoT platform was chosen as the IoT cloud to save the collected data updated over Wi-Fi to the Internet. A mobile GUI was designed to display the updated readings from the sensor and enable the remote control of the water pump using smartphones. The detailed research activities are illustrated in the flowchart of Fig. 1.

3.1. System modelling

The proposed system architecture of IoT–SIS–SPWP is described in Fig. 2. In the developed system, the sun rays are applied on two solar panels (50 W each) to generate the electrical power used to power the high-pressure auto diaphragm water pump with the DC motor set. The extra energy will be stored in the 12 V battery through the solar charger controller. The battery used is a Panasonic lead-acid 12 V, 7.5 Ah battery that copes with the micro diaphragm water pump. The battery capacity can supply electricity to the motor for up to 3 h whenever required during night irrigation activities. The microcontroller collects the data from the utilized sensors and sends it to the Blynk IoT cloud server over the Wi-Fi interface of the NodeMCU and, at the same time, forwards the farmer's switching commands to the SPWP. The NodeMCU connects to the Internet via the nearest Wi-Fi access point. The farmer will be able to remotely monitor the surrounding conditions in the farm (soil moisture, temperature, and humidity) using the GUI based on the Blynk mobile application through Internet-connected smartphones. The sensors are connected to the input GPIOs of NodeMCU, and a four-channel relay module is connected to the output GPIOs. The farmer also can receive notifications for abnormal conditions via the same app. when some threshold values are exceeded.

Accordingly, the farmer can switch ON/OFF the solar-powered water pump for irrigation purposes when needed. The DC pump is a water-pressure diaphragm pump of 12 V, 8 A, and 100 W. The maximum output water pressure is 0.8 MPa with a maximum flow rate of 6.5 L per minute. The pump is connected to a hose pipe with multi-nozzles to spry the water during the irrigation process at different pressure and flow rates. Also, the pump is coupled with a water filter to improve the irrigation water quality for keeping plants healthy and in good condition. The mobility support of the system allows its movement and reallocation based on demand.

3.2. System design

The IoT–SIS–SPWP system layout has been designed using NX10, as shown in Fig. 3. The parts or components of the SPWP are a polypropylene luggage toolbox (the overall body), two solar panels 50 W, a hose pipe's hook, an extendable holder, and a cover box to store electrical components of the IoT-SIS, metal support, battery, and water pump. It also shows the dimension of the overall parts of the IoT–SIS–SPWP. We aim to build an ergonomic design of a solar water pump to fit the people who use this water pump. Proper ergonomic design is necessary to prevent repetitive strain injuries and other musculoskeletal disorders. It is relevant in designing such things as safe furniture and easy-to-use interfaces. The solar water pump is more compactable and lightweight. The luggage design makes this water pump portable, and the size is ergonomic and suitable for smallholder irrigation. The design of this portable solar water pump is inspired by wheeled travel luggage.

The designed IoT–SIS–SPWP system will be used in the area alienated from the electricity grid. The implementation of solar power would reduce energy costs such as fuel and electricity. The usage of solar power benefits long-term savings, but it also promotes the usage of renewable energy and reduces pollution. However, the usage of solar energy has a major challenge which is theft. Making the system portable is beneficial as it could be transported anywhere and stored safely in storage.

The water pump body is made of polypropylene. Polypropylene is a rugged and highly chemical-resistant material often used as material for toolboxes. It has similar properties to polyethylene but is more challenging and more heat resistant. Durable and lightweight making it suitable for encasing electrical equipment in a work environment with additional resistance to chemicals, making it suitable for usage in the marine environment. It is also heat resistant, which makes it suitable for usage under prolonged sunlight. Polypropylene seems to be destined to increase its importance as raw material for the production of plastics due to its excellent thermal and mechanical properties, low cost, and versatility of uses.

For the hose, we use Polyvinyl Chloride (PVC) garden hose with polyester fibre reinforcement. This hose has excellent chemical and physical properties, very ideal for conveying water, widely used in construction, agriculture, fishery, project, household, and industrial service. It could handle temperatures ranging from -10 °C to $+65$ °C. PVC hose also has good abrasion resistance making it suitable for a rugged environment. Since there are many types of hose based on oil-resistant elastomers and many specifications for each type, sometimes with conflicting requirements, it is impossible to generalize regarding current uses or future trends. PVC blends are used in covers when excellent abrasion resistance is required. We use a portable water filter with hollow fibre membranes (HFMs) as filter material for water filtration. HFM was initially developed in the 1960s for reverse osmosis applications; it has become prevalent in water treatment. HFM could ensure that no pathogens can slip through removing substances such as Bacteria, Protozoa, E. Coli, Giardia, *Vibrio cholerae*, Salmonella Typhi, Leptospirosis, and microplastics.

The amount of solar energy collected by a solar panel is a function of local solar radiation, ground reflection property, and collecting a panel's tilt and orientation. The orientation and the tilt of a solar panel strongly affect the amount of the collected yield. Therefore, solar panels must be slanted and oriented at optimum angles to collect the maximum solar energy available in a specific region. The best method to optimize the tilt and the orientation of a solar panel is by applying an active sun tracker. Active sun trackers are electromechanical or pure mechanical devices that keep changing the tilt and the orientation of a solar panel/solar array periodically during the day. However, the capital cost of such a system is high, and it consumes energy during tracking. Thus, changing the tilt angle and the orientation monthly, seasonal, or yearly for a photovoltaic (PV) panel, as in our system, maybe more feasible than applying an active sun tracker.

3.3. System fabrication

After the design phase, we started the fabrication and installation phase of the portable solar water pump since it is the central part of the proposed system. Besides that, the structural analysis is compulsory to ensure that this design can support all the load weight. Next, the type of material used to build the water pump frame is identified and obtained from the supplier. After that, the inspection was conducted immediately after the material was received to avoid any defects happening. The overall fabrication process sequence is illustrated in Fig. 4. Basic manufacturing processes, including welding, grinding, cutting, and many others, have their safety precautions. Extreme caution should be exercised when using any tool to prevent injury to personnel. While working in a machines room, rules and regulations need to be obeyed for our safety. Safety measures need to be taken into account at our workplace are likes wearing safety boots, jackets, face shields, and gloves when handling tools and machines. The machinist should not wear a watch, jewellery, other accessories, or loose clothes that can cause trouble to them when handling the machine. Every different type of operation on machines must be conducted followed by the correct procedure and tools

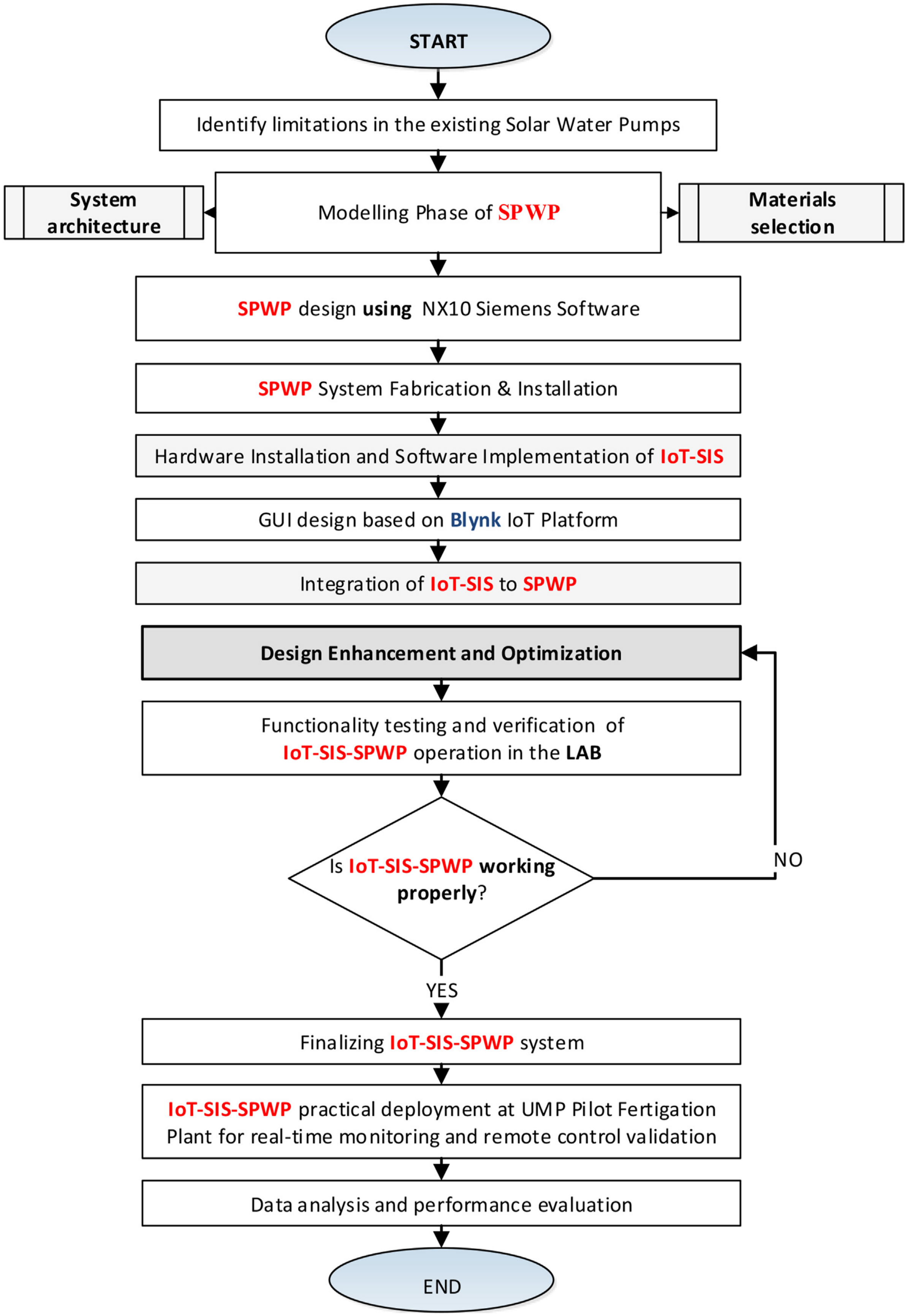


Fig. 1. Flowchart of research activities.

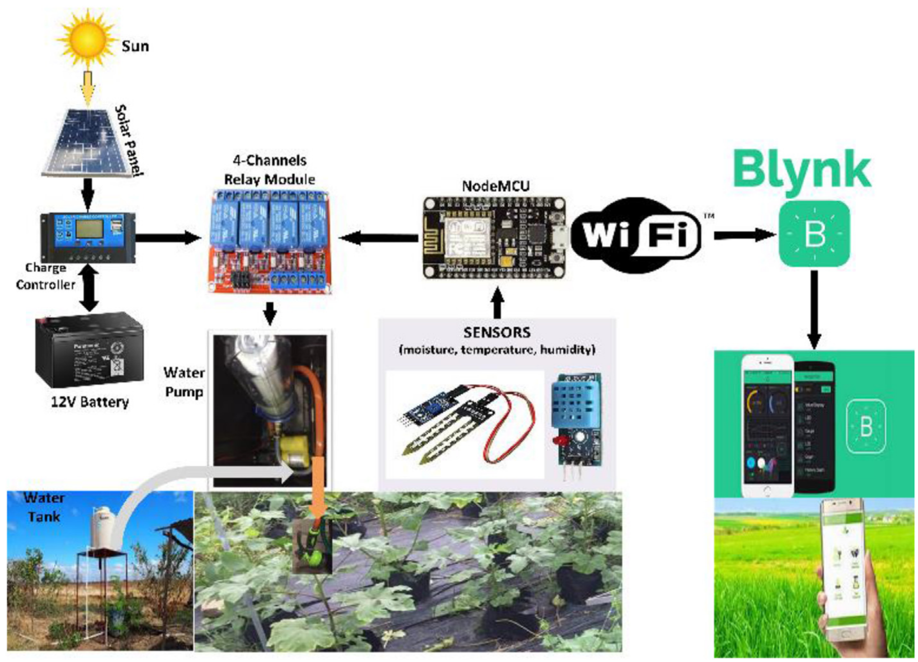


Fig. 2. Overall system architecture.

to avoid accidents happening in the machine room. The floor must always dry to avoid slipperiness, and the table must be cleaned repeatedly. For metal support, firstly, the mild steel bar is cut into four parts. Then, the metal bar edges are ground and polished using a grinder and sander. The metal was then welded together and fitted onto the luggage box using a drill and rivet.

For PV panels, two PV panels are attached using screws and hinges, and a slider is attached on the top and bottom of the solar panel. Then, sheet metal is sheared and bent using a shearing machine and press brakes. The PV Panels, sheet metal, and luggage box are attached using screws, rivets, and L-section. Then, the placements of the filter and pump and the box containing microcontrollers, as shown in Fig. 5. Then, the solar controller and hose hanger are attached to the solar water pump sides, as shown in Fig. 6. For final adjustment, L-section is attached to parts for durability. Latches are added to the solar panel to avoid turning when transporting. Fig. 7 depicts the finished system product of the solar-powered water pump with the implemented IoT-SIS controller.

3.4. Components selection

Hardware and software components are crucial and essential in the design of IoT systems. NodeMCU ESP8266 is used in our system as it is a single-board microcontroller intended to make the application of interactive objects or environments more accessible. It is a cost-effective and open-source physical computing platform with an extensible software development environment for board programming. It is used to gather data read by the sensors and upload the data to the MQTT server. Besides, it also receives commands given by the user to do specific tasks via the MQTT server. NodeMCU consists of a physical programmable circuit board like any other development board, such as Arduino and Raspberry Pi.

This microcontroller can be used to develop interactive objects, taking inputs from various switches or sensors and controlling a variety of relays, lights, motors, and other actuators. We use NodeMCU ESP8266 as the microcontroller to enable farmers to observe sensor readings and pass the command towards the water pump. The NodeMCU is attached with a Wi-Fi interface to be connected to the Internet via a hotspot. NodeMCU has 17 GPIO pins that can be allocated to different functions such as I2C, I2S, UART, PWM, IR remote control, LED light, and button programmatically. Thus, it is a good candidate for IoT applications with a limited number of sensors and actuators like our system. NodeMCU has a ready-to-use structure as it comes in a complete package form, including the 5 V regulator, a burner, an oscillator, a micro-controller, a serial communication interface, LED, and headers for the connections. The programming of the NodeMCU can be done by using Arduino software, an Integrated Development Environment (IDE), to write the code of instructions and upload it to the microcontroller.

For NodeMCU, a beginner would need to learn a new programming method different from Arduino but much easier. This is because the programming environment is easy to use for beginners yet flexible enough for advanced users to take advantage of. The required coding to initiate the connection between NodeMCU, sensors, and actuators can be developed via Arduino IDE and uploaded to the NodeMCU memory. It represents the heart of IoT systems since it acts as a sensing node and a gateway simultaneously. We have used the Wi-Fi module to create a mobile application to remotely control the water pump on and off operation from smartphones. A mobile application to monitor and control the system has been created. It can be used from anywhere and anytime over an internet connection. The real-time monitoring and control will lessen the user's burden and increase the efficiency of the water pump.

Soil moisture sensor measures the water content in the soil. The relation between the measured property and soil moisture must be calibrated and may vary on environmental factors such as soil type, temperature, or electric conductivity. Reflected microwave radiation is affected by soil moisture and is used for remote sensing in hydrology and agriculture. Farmers or gardeners can use portable probe instruments. Soil moisture sensors typically refer to sensors that estimate volumetric water content. Another class of sensors measures another property of moisture in soils called water potential. The FC-28 soil moisture sensor is mounted at the side of the system to measure the soil moisture at the farm. This module also includes a potentiometer that will fix the threshold value, & the comparator-LM393 can evaluate the value. The LED will turn on/off based on the threshold value. The sensor needs to be placed into the soil, and the measurement of the soil moisture will be exposed and then data uploaded to the Blynk application.

DHT11 is a primary, ultra-low-cost digital temperature and humidity sensor. It uses a capacitive humidity sensor and a thermistor to measure

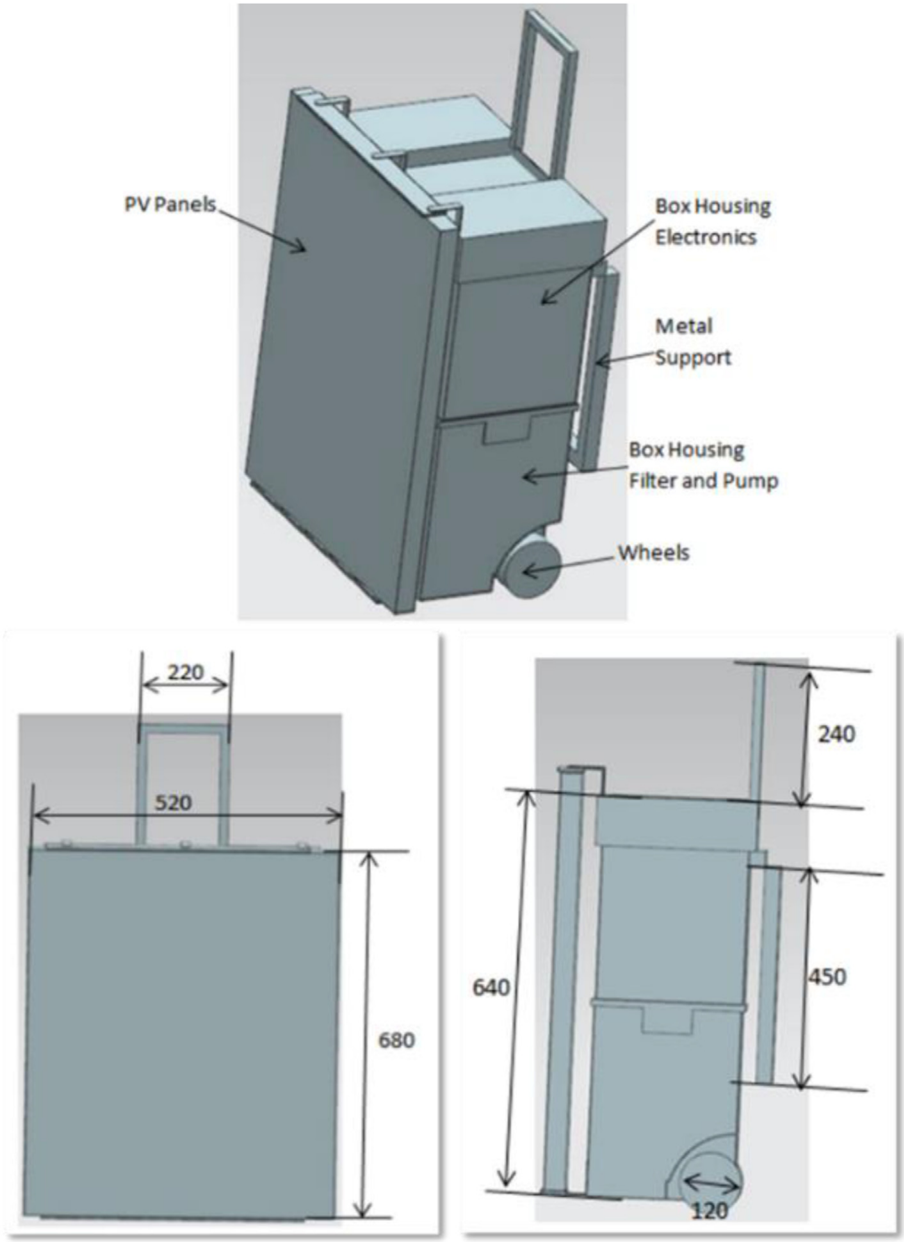


Fig. 3. System design dimensions.

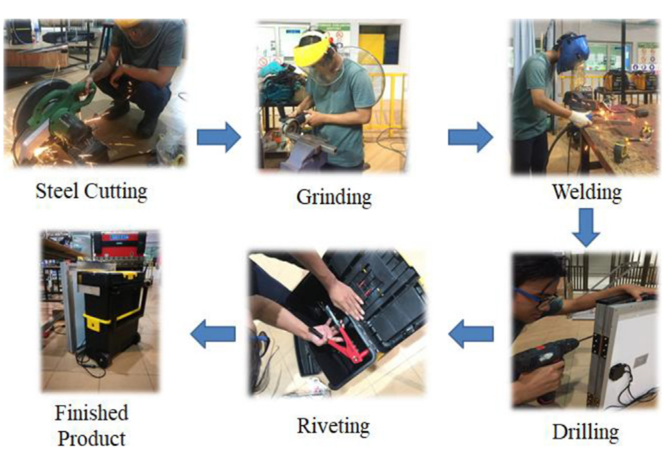


Fig. 4. System fabrication phases.

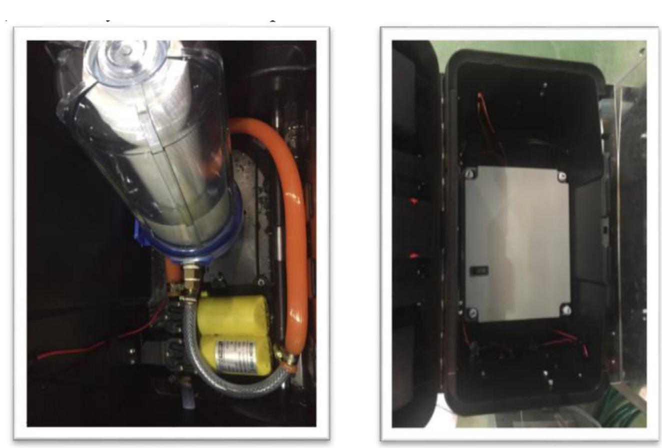


Fig. 5. Placement of filter, pump, and microcontroller box.

Fig. 6. Solar charge controller and hose hanger.

the surrounding air and spits a digital signal on the data pin (no analogue input pins are needed). It is relatively simple to use but requires careful timing to grab data. The only real downside of this sensor is that it can only update new data once every 2 s. The sensor is utilized in our system to measure the surrounding temperature and humidity. DHT11 with its jumpers are mounted at the side of the prototype, upper the toolbox in a drilled hole. Thus, the DHT11 sensor can be exposed to the surrounding temperature and measured to be uploaded to the Blynk application. DHT11 sensor has four pins- V_{CC}, GND, Data Pin, and a not connected pin. A pull-up resistor of 5 k to 10 k ohms is provided for communication between the sensor and the microcontroller.

A 4-channel 5 V DC relay module is exploited in this study to perform the switching of the pump and any other actuators if necessary. It can also be used to control various appliances and equipment with a large current. The relay is energized or reenergized based on the received signals from the NodeMCU depending on the farmer's commands. It is equipped with high-current relays that work under AC 250 V 10 A or DC 30 V 10 A. It has a standard interface that can be controlled directly by the microcontroller.

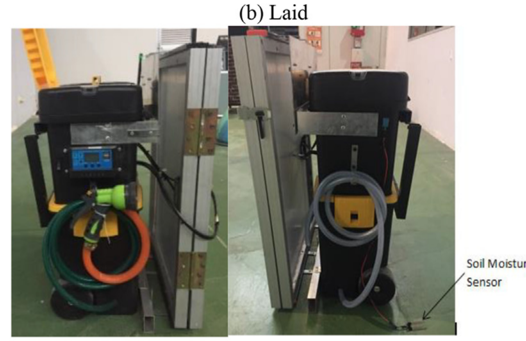
The Arduino IDE is a cross-platform application that is written in the C++ programming language. It is used to write and upload programs to Arduino-compatible boards, but also with the help of third-party cores, and other vendor development boards. It connects to the Arduino and Genuino hardware to upload programs and communicate with them. Support for third-party hardware can be added to the hardware directory of the sketchbook directory. Platforms installed may include board definitions (which appear in the board menu), core libraries, bootloaders, and programmer definitions. Coding for this project has included all types of sensors, including DHT11 sensors and soil moisture sensors. The specific library of all these sensors has been applied to ensure all the sensor is working correctly. Next, the ESP8266 NodeMCU's library has been included in the program for the communication feature between the user and the microcontroller system. AT command has been used as the tool to send feedback and receive a command from the user.

3.5. Circuit design and installation

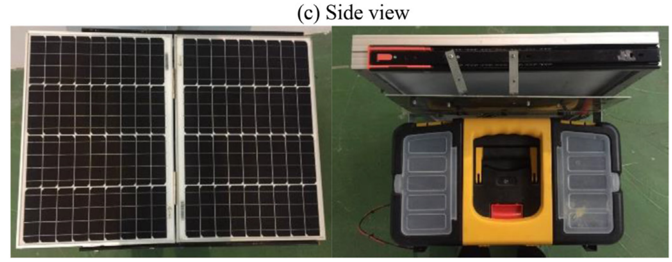
As stated earlier, the proposed solar-powered water pump has been fabricated—this phase is devoted to the description of hardware and software development of the proposed IoT-SIS system. The selected electrical/electronic components need to be connected to form the control circuit installed in the controller box of the developed IoT–SIS–SPWP. This control circuit will be used to monitor and control the fabricated solar-powered water pump over the Internet. The control circuit is installed into the controller box after finishing the testing and verification. Before that, all components are connected according to the schematic diagram as shown in Fig. 8, which also illustrates the virtual connection of electrical components using Fritzing software.

(a) Stand

(b) Laid



(c) Side view



(d) Top view

Fig. 7. Finished IoT–SIS–SPWP system product.

Then the components are installed on the breadboard to confirm that the circuit works correctly before finalizing the connections and attaching them to the entire system. As shown in Fig. 9, the developed IoT control system of the solar-powered DC water pump motor set is equipped with a 5 V power source, NodeMCU ESP 8266 Wi-Fi module, soil moisture sensor, temperature/humidity sensor, and relays. After successfully testing each component individually, all the components were assembled and connected to the NodeMCU. The required coding has been developed using Arduino IDE. LED was used as the replacement for the actual pump to check sensor functionality. During this phase, many tests have been conducted, and improvements have been suggested when necessary. The errors and problems that we faced during the testing

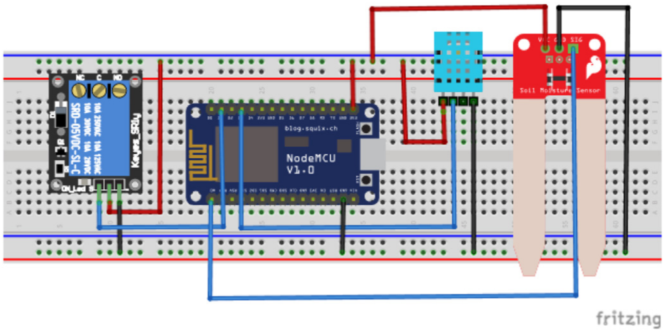


Fig. 8. Circuit diagram of the system.

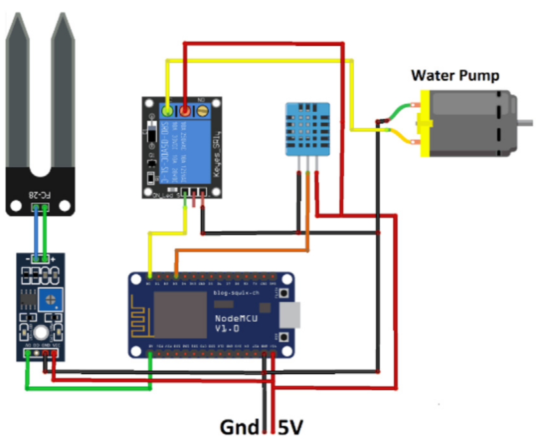


Fig. 9. Control circuit with the DC water pump.

procedure were identified and fixed. This step was repeated until a successful product was obtained. After compiling all the programming codes into the NodeMCU, the actuators (relay module and DC motor) were used for the practical testing by implementing the circuit to the proposed system, as shown in Fig. 10. A GUI based on the Blynk IoT platform has been developed to display the gathered information from sensors and allow the farmer to control the water pump using a smartphone.

As an example of the improvement and optimization process, initially, the reading from the sensors was unable to be uploaded to the Blynk application server. The reading can only be viewed on the serial monitor of the Arduino IDE software. The relay module could only switch on/off by the sensors themselves when a certain requirement was triggered. After some reconstruction of the coding, the reading obtained from the sensors could be updated on the IoT server. The problem of uploading and fetching the data was solved, but the relays were acting the opposite way from the user's command. When the user remoted the relay to turn on via mobile apps or pc, the relay was turned off instead. Hence, the coding for receiving the command from the server for turning on/off the relay was remodified. The portable solar water pump was placed in the direction that sunlight incident directly on the solar panel. The solar water pump was connected and controlled by the application on the mobile phone.

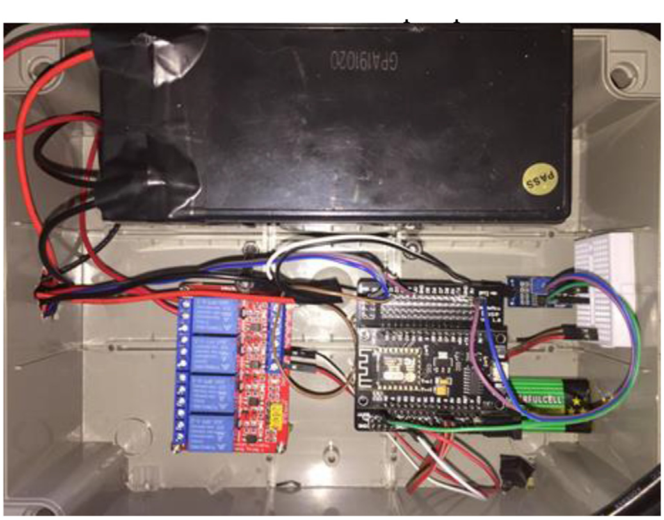


Fig. 10. Installation of all components in the controller box.

3.6. System operational procedure

The temperature and humidity sensor and soil moisture sensor send the collected data directly to the microcontroller via the connected wires. The NodeMCU receives and uploads data to the Blynk server using the Wi-Fi module. After the program coding was uploaded in the NodeMCU, the data can be accessed using any device, mainly smartphones with Internet access in this case. In our coding, we have developed an algorithm to gather the information from the sensors and passed to the cloud as in *Algorithm* 1.

The system operates based on the developed coding in the microcontroller. The water pump is set to turn on using Blynk mobile application. The sensor readings would be detected and set up in the coding to measure the surrounding of the farm and the operation hour of the water pump. According to the Blynk application, the readings of moisture, temperature, and humidity will be displayed based on the unit decided by the user. The farmer will observe the sensors' readings in real-time, and according to predefined threshold values, he will be able to decide whether to switch on/off the water pump. The IoT server will receive the command from the Blynk GUI on the farmer's smartphone or the Blynk homepage and send the command to the microcontroller to switch on/off the water pump using the application. It will be sent to the microcontroller to switch on the relays. Thus, the water pump status and the reading of sensors are displayed on the application to check the farm's surroundings or where the testing took place. If the relay is energized, the water pump will be switched on. Then, the water flow starts from the pump to the filter and next to the irrigation system as planned. When the user presses the switch-off button on the GUI, the water pump will be turned off.

Algorithm 1. Monitoring and control algorithm for IoT–SIS–SPWP

Algorithm 1 Monitoring and control algorithm for IoT-SIS-SPWP

Require: If soil moisture is low or temperature high: switch-on water pump remotely
Ensure: Real-time monitoring of surrounding conditions (moisture, temperature, humidity)

```
define Wi-Fi Access Point Username/PW ➲ (connect NodeMCU to the Internet)
define FC-28 & DHT11 libraries
include Blynk libraries
define NodeMCU.GPOI for FC-28 ➲ soil moisture sensor pins (Data, Vcc, GND)
define NodeMCU.GPOI for DHT11 ➲ temperature& humidity (Data, Vcc, GND)
define NodeMCU.GPOI for Relay module (outputs)
M ← Soil moisture ➲ From FC-28 moisture sensor
T ← Temperature value ➲ From DHT11
H ← Humidity value ➲ From DHT11
M_TH ← Moisture Threshold value
T_TH ← Temperature Threshold value
H_TH ← Humidity Threshold value
Initialize IoT-SIS-SPWP ➲ Switching ON the system at t = 0
NodeMCU acquires the data (moisture, temperature, humidity)
  for each round, do
    get M, T, H
     if M <= M_th || T >= T_TH || H>= H_TH then
     send a notification to the farmer via Blynk
     switching-ON the SPWP remotely via Blynk
     else
     switch-OFF the SPWP
     return moisture, temperature, humidity values, and pump status
    end if
    Send data to Blynk Server over the Internet of NodeMCU
   Retrieve data in Blynk App using Smartphone
 end for
```

4. Experimental results and validation

The SPWP-IoT-SIS system has been designed and fabricated, as stated in the previous section. In this section, the system's functionality and performance will be tested and evaluated. We have conducted practical experiments in two different environments to evaluate multiple criteria, including water quality, flow rate, energy consumption, and IoT system functionality. We have successfully tested the developed system in both offsite and onsite testing in this context. The offsite testing was held at the LAB and workshop, while the onsite testing was held at UMP Pilot Fertigation Farm. Before starting the system development, a site visit was conducted to obtain information regarding the farm. Our system prototype could be deployed at the farm to check its applicability and compatibility in real environments. From the site visit, we get information on the coverage area of the farm, the fertigation way that is used at the farm, the quantity of the plants on the farm, the type of water pumping system used in the farm, and the system operation hour. Since our system composes several main components including a solar panel, DC motor, water pump, water filter, irrigation nozzles, and IoT-system components, several tests were conducted.

4.1. Experimental setup

The proposed SPWP-IoT-SIS system was placed at the UMP Pilot Fertigation Farm during the onsite testing phase, as shown in Fig. 11. The University Malaysia Pahang (Gambang area) latitude is 3°43′23 North, and the longitude is 103°7′16 East. The system is powered on and connected to the Internet via a Wi-Fi access point. The DC water pump was connected to the solar panel. After attaching the inlet port of the pump with a suction pipe, priming was done. The inlet port of the solar water pump was connected to the water pump in the irrigation system of the Fertigation Farm. Another hose pipe was attached to the end of the outlet of the water pump. After that, the solar water pump was switched on via the Blynk GUI by using the mobile phone.

4.2. Power and water flow rate comparison

In the first step, we have devoted our focus to determining and comparing the generated power from the solar panel with respect to irradiance for different water flow rates of the pump. The system has two solar panels with 50 Watts per panel. In the onsite testing and offsite system testing, the proposed solar water pump performance has been observed, measured, and evaluated. The voltage, current, and power consumed by the water pump and the flow rate of the water pump were measured and recorded. The DC water pump is designed on the basic requirement of the agriculture product. The power of the pump is obtained from Eq. (1):

$$\text{Power consumed by pump } (W), P = V \times I \tag{1}$$

where V is the DC voltage, I is the current, and P is the power of the water pump.

As stated earlier, our SPWP is attached with multi-nozzles to control the water flow rate and a filter for purifying the irrigation water. Such features enable our system to conveniently cover a wider area and diverse plants using a portable pump.

The system can pump the water at different flow rates using six nozzles: cone, quad, fan, flat, soaker, and jet. Each nozzle type has a different water flow rate and required a specific amount of power. Water was discharged, and its volume was measured to determine the water flow rate according to Eq. (2), where 6 L of water are collected, and the time taken to collect the water is estimated.

$$\text{Flow rate, Q} = \frac{\text{water discharged (litres)}}{\text{time taken (min)}} \tag{2}$$

The six types of nozzles' performance are analyzed in terms of flow rate, voltage, and power. The data is collected and tabulated to compare the voltage, power, irradiance, and flow rate of six different types of nozzles, as listed in Table 1. The obtained results for the voltage measurements are between 11.0 V and 11.8 V, while the current is between 6.8 and 7.3 A. The power is roughly between 74.8 W and 86 Watts. The difference between the highest value and the lowest value for the voltage, current, and power readings is typically based on the different irradiance received by the panel during each nozzle type and the impact of the flow rate of each nozzle. From the table, it can be seen that the voltage and the power for the cone nozzle are the highest compared to the other five nozzles. The voltage, current, and power for the cone nozzle are 11.8 V, 7.3 A, and 86.14 W, respectively. This data proves that the solar panel absorbs more sunlight irradiance, thus providing more voltage, current, and power than the other five nozzles. While for the jet nozzle, the electrical parameters have the lowest readings compared to the other nozzles. The voltage, current, and power readings are 11.0 V, 6.8 A, and 74.8 W. This data proves that the solar panel absorbs less sunlight and provides less voltage, current, and power compared to the other five

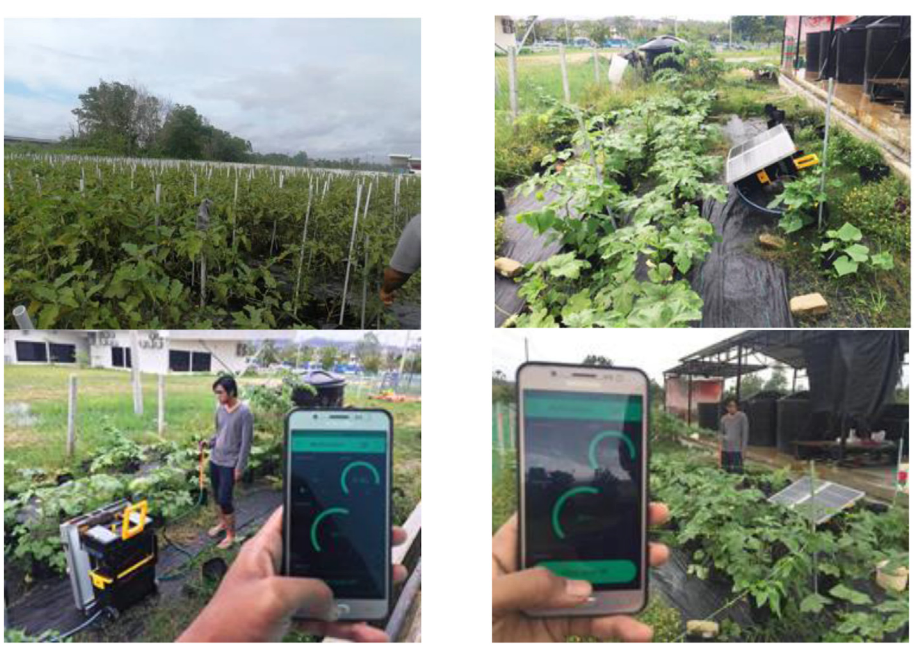


Fig. 11. Onsite system setup.

Table 1
Data for each nozzle.

Type of nozzle	Irradiance (W/m^2)	Voltage (V)	Current (A)	Power (Watt)	Water Discharge (Liter)	Time (min)	Flow Rate (L/min)
Cone	929.8	11.8	7.3	86.14	6	1.43	4.20
Quad	926.5	11.8	7.2	84.96	6	1.45	4.14
Fan	916	11.7	7.0	81.90	6	1.50	4.00
Flat	909.6	11.4	7.1	80.94	6	1.55	3.87
Soaker	897.3	11.3	6.8	76.84	6	1.77	3.39
Jet	810.7	11.0	6.8	74.80	6	2.00	3.00

nozzles, as shown clearly in Fig. 12.

Based on the trend of the growth data of the irradiance reading, as the solar irradiance increases, the power generated by the solar panel will be higher and more power will be supplied to the water pump with different nozzles. Fig. 13 depicts the comparison between the electrical power supplied by the solar panel to the water pump and the water flow rate for different nozzle types.

The experiment is conducted in the afternoon from 13.00 until 17.00, which has more sunlight. The flow rate of the water pump is measured in L/min. The water pump's discharge was measured by a volumetric method by collecting 6 L of water in a container. The subsequent time taken to fill up the container was recorded using a stopwatch. The same was repeated for the other five nozzles, and the average of all the nozzles was considered.

As shown in the figure, the maximum flow rate has occurred with the cone nozzle, which is 4.20 L/min due to the highest generated voltage by the panel, 11.8 V. The cone nozzle required 1.43 min to discharge 6-Liter water. This flow rate indicates that the solar panel supplied more power to the cone nozzle causing the cone nozzle to have the highest flow rate. However, the jet nozzle has the minimum flow rate among the six nozzles, due to there being slightly unstable voltage causing less power to be used by the jet nozzle. The jet nozzle required 2.00 min to discharge 6 L of water. Hence, the flow rate for the jet nozzle is 3.00 L/min. From the graph, it can be concluded that the higher the power supplied to each type of nozzle, the lesser time is used to discharge the water, and the higher the flow rate can be achieved. The second highest flow rate occurred with the soaker nozzle, which required 1.45 min to discharge the 6 L of water. Hence the flow rate for the soaker nozzle is 4.14 L/min. The flow rate for the soaker nozzle is very close to the cone nozzle. These values prove that the power supplied to both the cone nozzle and soaker nozzle is almost the same. The supplied power is stable for the cone nozzle and soaker nozzle.

4.3. IoT–SIS–SPWP validation

The IoT–SIS–SPWP system allows the user to remotely control the solar-powered water pump for irrigation using an Internet-connected smartphone. The Blynk IoT platform has been integrated into the mobile irrigation application, and a developed dashboard can be used to monitor and control the proposed system. The Blynk application allows the user to monitor soil moisture, temperature, and humidity. It also enables the remote control of the SPWP over the Internet at any time from anywhere. Fig. 14 depicts the developed GUI that we initially used to control the water pump over IoT and monitor the surroundings in the farm during the onsite testing.

This GUI has been developed and integrated into the Arduino IDE coding uploaded to the t NodeMCU ESP8266 microcontroller. Such GUI can be improved and expanded by including more widgets and indicators for any suggested improvements like adding more sensors for monitoring (raindrop and flow rate) or more actuators to control the solenoid valve. The data measured from the soil moisture sensor and temperature & humidity sensor can be obtained in the Blynk application. The application is synchronized and displays readings that are uploaded by the NodeMCU microcontroller in the IoT–SIS–SPWP system. The soil moisture sensor will detect the soil moisture on the farm to notify the user to turn on the water pump according to the soil moisture condition. The same goes for the temperature & humidity sensor to detect the surrounding places for the user to turn on and off the water pump at the farm. The data readings of the sensors are displayed in real-time.

The user needs to install the Blynk App. which is compatible with Android and iOS operating systems of smartphones. It can be downloaded from the Apps stores of any mobile phone. The application's name is "Blynk," which is synchronized with the IoT server Blynk account. During the synchronization process, the targeted server address is required, followed by the host port, the username, and the specified authentication token given by the server. Onetime information regarding the hotspot will be configured in the coding to connect the system to the

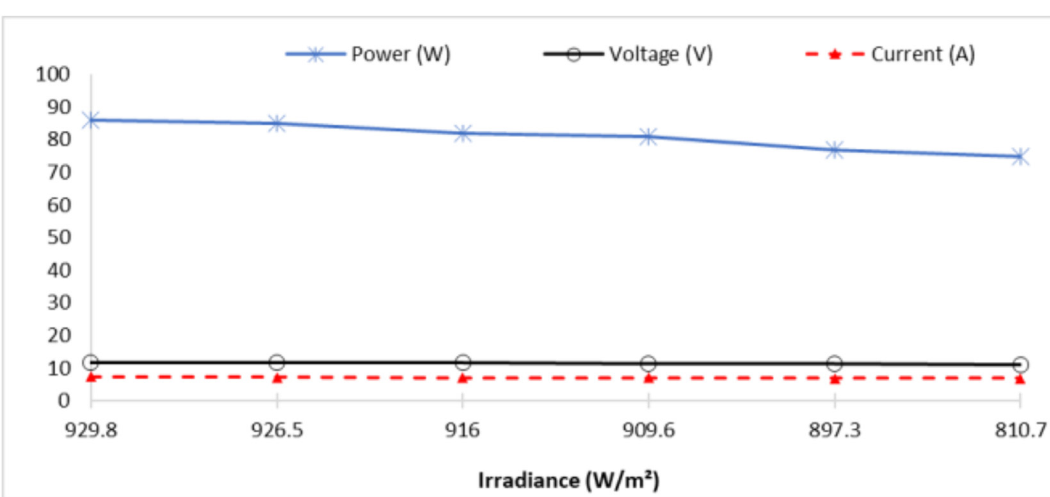


Fig. 12. Impact of solar irradiance on SPWP electrical parameters.

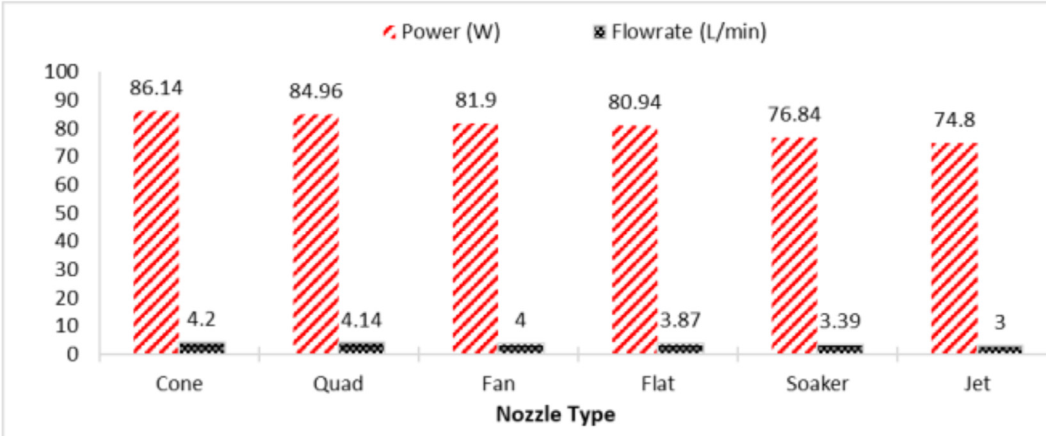


Fig. 13. Power vs. water flow rate for various nozzle types.

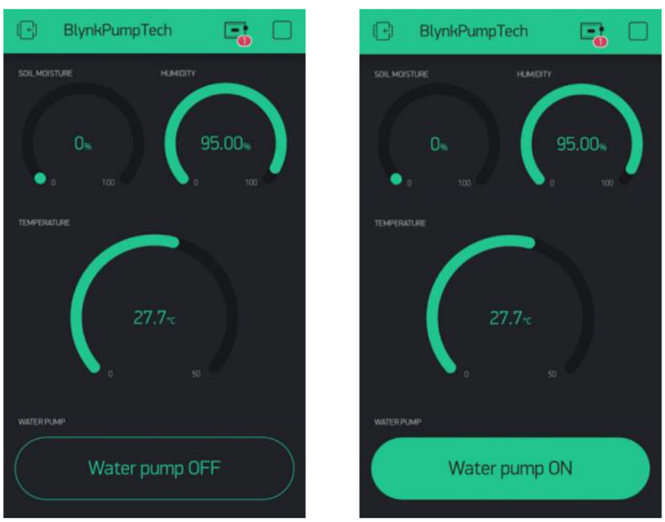


Fig. 14. Blynk GUI dashboard.

Internet. As the device is connected to the Internet, the Blynk application is started up. All the readings and buttons of the GUI could be viewed and activated. The water pump switch icons would turn green whenever the system was turned on, while the icon turned black would indicate the water pump was off.

From the figure, three displayed blocks could be found with some values. Those blocks were the place where the data from the sensors would be uploaded. The humidity and soil moisture value displayed is in percentage while the temperature is in $^{\circ}C$. The system functionality and performance have been validated.

After completing the onsite testing of our system, we have done some improvements and optimization based on the recommendation and suggestions by UMP Pilot Fertigation Farm management. We have implemented one more sensor for raindrop detection in our system, and we have modified the coding and Blynk GUI accordingly. Implementing such a sensor is to increase the data reliability of other sensors that are almost related to each other, including moisture, raindrop, temperature, and humidity. Since our system is a part of an ongoing research project, the expansion and improvements based on feedback from the industry and society are considered. The current version of our system is still being improved to be implemented in a Palm Oil Farm in collaboration with the industry. The updated Blynk GUI is shown in Fig. 15. We can monitor more surrounding conditions, and notification functionality has been enabled.

5. Conclusion and future work

This study designed and fabricated a solar-powered and portable water pump with an IoT-controlled irrigation system, where sensors collect information about moisture, humidity, and temperature together for efficient monitoring and water pumping via a mobile application. We have considered several limitations in the conventional water pump to be solved in the proposed system: cost-effectiveness, saving energy, supporting pump mobility, facilitating remote monitoring and operation, and enabling IoT solutions in agriculture. For the coexistence of different microcontrollers used by various applications, we have selected the NodeMCU due to its low price, small size, low energy consumption, and good performance with Wi-Fi support. In addition, select the open-source Blynk IoT platform with a mobile application to receive the collected data from sensors and store it in the cloud. The developed portable solar water pump can efficiently use a renewable energy resource and be controlled remotely using smartphones. Six types of nozzles have been tested and evaluated regarding the implemented system's consumed energy and flow rate in a real environment. The cone nozzle has the highest power and flow rate among the six nozzles, while the jet nozzle has the lowest power and flow rate.

Furthermore, the exploited water filter succeeds in filtering the pumped water for irrigation purposes. Since this paper is a part of an ongoing project, in the future, more functionalities will be enabled, such as pump automation based on the sensor readings. More sensors can be added to monitor more irrigation-related parameters, such as water quality sensors, GPS, flow rate, and light sensors.

Furthermore, the developed Blynk-based dashboard can be extended by adding more gadgets and indicators. In this project, there are some limitations found during the testing phase. The circuit system requires a stable network connection. Whenever NodeMCU is disconnected from the network, it will try to reconnect the network. However, if the network is disconnected, the system will not be functioning. Thus, the utilization of long-range communication technology is among the considered improvements in our system in the nearest future. Besides that, the prototype's weight is unfulfilled to the target. The heavyweight could be due to the implemented two solar panels to supply more power to the system during the day activities and store some energy in the battery. However, the system's portability has decreased the weight effects and can be easily moved within the deployment site. Other than that, the system needs to be more automated to switch on/off the pump and the valve based on threshold values rather than remote control by the farmer. For example, we did not set a specific range of optimum temperature and humidity values of the surrounding; thus, we would not receive any notifications via the mobile application to activate the water pumping system. Therefore, a fully automated irrigation system with a minimum of manual requirements will be among our future works.

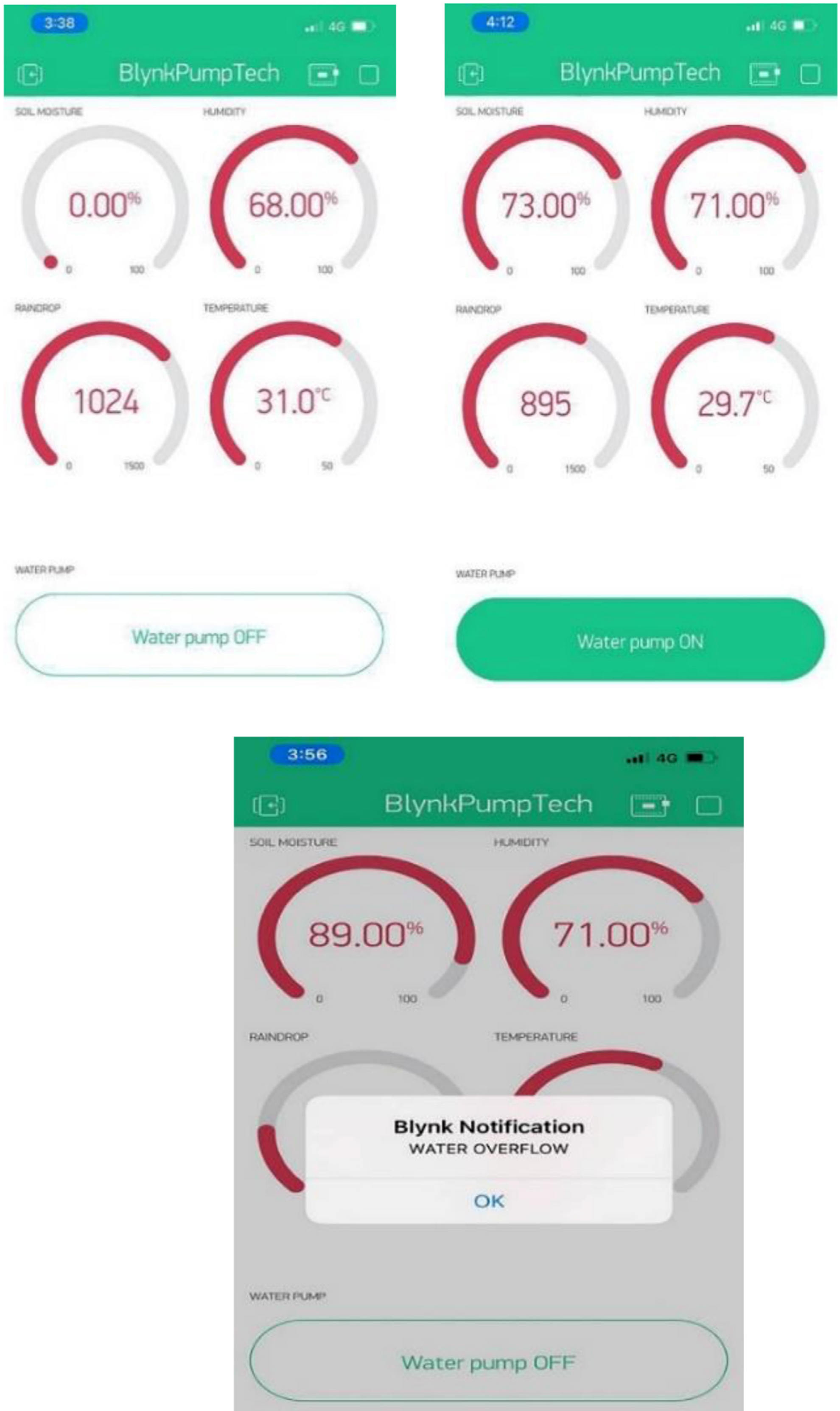


Fig. 15. The improved Blynk GUI dashboard.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The research was supported by Universiti Malaysia Pahang (www.ump.edu.my), Malaysia, under grant scheme No. RDU190397.

References

[1] T. Talaviya, D. Shah, N. Patel, H. Yagnik, M. Shah, Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides, Artif. Intell. Agric. 4 (2020) 58–73.
[2] D.A. Devitt, R.L. Morris, Selecting and Maintaining Trees for Urban Desert Landscapes: A Mojave Desert Water Conservation Perspective, iUniverse, 2020.
[3] A. Barman, B. Neogi, S. Pal, Solar-powered automated IoT-based drip irrigation system, in: IoT and Analytics for Agriculture, Springer, 2020, pp. 27–49.
[4] M.S. Bali, K. Gupta, K.K. Bali, P.K. Singh, Towards energy efficient NB-IoT: a survey on evaluating its suitability for smart applications, Mater. Today Proc. 49 (2022) 3227–3234.
[5] K. Shahverdi, E. Bellos, R. Loni, G. Najafi, Z. Said, Solar-driven water pump with organic Rankine cycle for pressurized irrigation systems: a case study, Therm. Sci. Eng. Prog. (2021), 100960.
[6] D. Adhikari, Policy review and analysis promoting solar-powered irrigation in India, IWRA (India) Journal (Half Yearly Technical Journal of Indian Geographical Committee of IWRA) 9 (1) (2020) 8–15.
[7] I. Manisalidis, E. Stavropoulou, A. Stavropoulos, E. Bezirtzoglou, Environmental and health impacts of air pollution: a review, Front. Public Health 8 (2020).
[8] M. Oberascher, W. Rauch, R. Sitzenfrei, Towards a smart water city: a comprehensive review of applications, data requirements, and communication technologies for integrated management, Sustain. Cities Soc. 76 (2022), 103442.
[9] K. Vohra, A. Vodonos, J. Schwartz, E.A. Marais, M.P. Sulprizio, L.J. Mickley, Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: results from GEOS-Chem, Environ. Res. 195 (2021), 110754.
[10] A.I. Lawal, I. Ozturk, I.O. Olanipekun, A.J. Asaleye, Examining the linkages between electricity consumption and economic growth in African economies, Energy 208 (2020), 118363.
[11] A.S. Pascaris, C. Schelly, L. Burnham, J.M. Pearce, Integrating solar energy with agriculture: industry perspectives on the market, community, and socio-political dimensions of agrivoltaics, Energy Res. Social Sci. 75 (2021), 102023.
[12] B.S. Pali, S. Vadhera, A novel solar photovoltaic system with pumped-water storage for continuous power at constant voltage, Energy Convers. Manag. 181 (2019) 133–142.
[13] A.N. Angelakis, et al., Irrigation of world agricultural lands: evolution through the Millennia, Water 12 (5) (2020) 1285.
[14] S.S. Kumar, C. Bibin, K. Akash, K. Aravindan, M. Kishore, G. Magesh, Solar powered water pumping systems for irrigation: a comprehensive review on developments and prospects towards a green energy approach, Mater. Today Proc. 33 (2020) 303–307.
[15] M. Aliyu, G. Hassan, S.A. Said, M.U. Siddiqui, A.T. Alawami, I.M. Elamin, A review of solar-powered water pumping systems, Renew. Sustain. Energy Rev. 87 (2018) 61–76.
[16] N. Lefore, A. Closas, P. Schmitter, Solar for all: a framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder agriculture, Energy Pol. 154 (2021), 112313.
[17] T. Chowdhury, et al., Energy, exergy, and sustainability analyses of the agricultural sector in Bangladesh, Sustainability 12 (11) (2020) 4447.
[18] P.K.S. Rathore, S.S. Das, D.S. Chauhan, Perspectives of solar photovoltaic water pumping for irrigation in India, Energy Strategy Rev. 22 (2018) 385–395.
[19] G. Li, Y. Jin, M. Akram, X. Chen, Research and current status of the solar photovoltaic water pumping system–A review, Renew. Sustain. Energy Rev. 79 (2017) 440–458.
[20] A.H. Yavuz, Solar thermoelectric generator assisted irrigation water pump: design, simulation and economic analysis, Sustain. Energy Technol. Assessments 41 (2020), 100786.
[21] S.R. Mulmane, R. Khamitkar, Automation of water pump controller for irrigation using ATMEGA 16, IOSR J. Electron. Commun. Eng. (2015) 128–134.
[22] M. Hadwan, A. Alkholidi, Assessment of factors influencing the sustainable performance of photovoltaic water pumping systems, Renew. Sustain. Energy Rev. 92 (2018) 307–318.
[23] A. Nikzad, M. Chahartaghi, M.H. Ahmadi, Technical, economic, and environmental modeling of solar water pump for irrigation of rice in Mazandaran province in Iran: a case study, J. Clean. Prod. 239 (2019), 118007.
[24] V. Zavala, R. López-Luque, J. Reca, J. Martínez, M. Lao, Optimal management of a multisector standalone direct pumping photovoltaic irrigation system, Appl. Energy 260 (2020), 114261.
[25] A. Al-Ali, A. Al Nabulsi, S. Mukhopadhyay, M.S. Awal, S. Fernandes, K. Ailabouni, IoT-solar energy powered smart farm irrigation system, Journal of Electronic Science and Technology 17 (4) (2019), 100017.
[26] A. Reghukumar, V. Vijayakumar, Smart plant watering system with cloud analysis and plant health prediction, Procedia Comput. Sci. 165 (2019) 126–135.