



Development and Testing of an Automated Solar-Powered Nutrient Film Technique (NFT) Hydroponic Planting System

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Abstract

This paper presents an automated solar-powered Nutrient Film Technique (NFT) hydroponic system designed to address the major challenges of global food security and sustainable agriculture. With the global population projected to reach 9.3 billion by 2050, conventional agriculture is unlikely to meet the pressure - land, water, and energy are all in short supply and at a premium. The system proposed here is an intelligent integration of renewable solar energy and IoT-based automation with the objective of extracting maximum benefit from the available resources while providing better crop yields. There are three primary subsystems: an 80W solar power system with an MPPT charge controller and 12V batteries, an NFT hydroponic system constructed with 3" PVC channels and a 12V DC nutrient pump, and an automation system created using an Arduino Nano microcontroller, an ESP8266 Wi-Fi module, NPK, and water level sensors. The system harvests data, uploads it to the Thingspeak IoT platform for real-time telemetry, command, and control services. In the field, performance trials showed that the system performed well, maintaining target nutrient levels (nitrogen: 100-130 ppm, phosphorus: 34-37 ppm, potassium: 168-173 ppm) while slashing water consumption by a whopping 90 percent compared with the existing technique. The use of solar energy and independence from the power grid, along with automatic management, avoided manual handling, resulting in accurate environmental conditions. The resultant watering and environmental changes were done as scheduled, ensuring the maintenance of stable plant health. Overall, this study provides a practical and energy-saving approach for urban agriculture, especially for those land-limited and uneven-power-supplied regions. There is plenty of room for further research and development, AI optimization, new types of energy storage, and full-blown cost estimates could help scalability.

Keywords: Solar-powered hydroponics, NFT system, automated agriculture, IoT monitoring, sustainable farming.

1.0 Introduction

The global population continues to rise daily and is projected to hit 9.3 billion by 2050 [1]. As the world's population continues to grow, the availability and accessibility of wholesome food have become a critical issue that directly affects a nation's overall well-being and economic stability [2]. Consequently, there is a pressing need to boost crop production to ensure an adequate food supply. More arable land is needed for food production due to the growing demand for housing the sudden expansion of the global population; therefore, there is now a greater need than ever for food production to meet people's nutritional needs [3], [4]. This growing demand for food requires the use of more energy, water, and soil resources, which can have adverse environmental effects.

According to [5] the mass adoption of intensive farming practices can result in soil degradation, nutrient depletion, and reduced soil fertility, ultimately endangering the land's long-term productivity. As a result, various modern farming techniques have been developed to minimize water usage and the land area required for cultivation, with hydroponic farming being one of the most well-known approaches. As reported by [6] hydroponics is a method that utilizes water and nutrient solutions as the growing medium, enhancing productivity by closely monitoring environmental factors in comparison to conventional farming techniques.

In a hydroponic setup, plants are placed in containers, with their roots suspended in a nutrient-rich liquid, enabling them to grow quickly and develop a dense root network. [7] highlights the advantages of modern agricultural systems such as hydroponics, aeroponics, and aquaponics, over conventional ones. These systems use nutrient-rich water, require less water and space, and can employ vertical farming, thereby increasing yields. These systems also offer water efficiency and can support continuous production throughout the year. Hydroponics can produce higher yields by utilizing both horizontal and vertical space, thereby increasing plant density, and meeting consumer demands for nutritious fresh products [8]. It also minimises environmental impact and uses less land and water than traditional agriculture, using smart greenhouses for precise control of plant physiology.

A hydroponics monitoring system using an ESP32 microcontroller and sensors such as TDS, pH, water level, and temperature was developed by [9]. The system automatically activates water or salt pumps to drain necessary materials into the plant basin. The user can view hydroponic parameters through the Blynk app on a smartphone

and activate pumps if required. The system and IoT interface were successfully built and implemented, enabling users to check system parameters and activate pumps if needed. Also [6] developed an indoor automatic vertical hydroponic system that doesn't rely on the outside climate.

The system, which uses a microcontroller and an open Internet of Things (IoT) platform, can grow common crops without requiring a large amount of space. The system offers real-time notifications, enabling users to monitor parameters remotely. The system can be used for quantitative optimization and automation of labour-intensive maintenance activities. According to [10] the use of electricity in agriculture has many benefits; however, it also has drawbacks with regard to electricity use, such as high upfront costs, equipment failure risk, and the requirement for steady power to sustain ideal growing conditions. Additionally, some systems may require a lot of electricity for pumping, heating, and lighting, which would raise overall energy usage. To overcome these problems, there is a need to develop an automatic solar-powered NFT hydroponics system. This research aims to develop and test the performance of an automated solar-powered NFT hydroponic system designed to enhance energy efficiency, lower operational costs, and improve crop yield.

2.0 Materials and Methods

2.1 Machine Description

The developed automated solar-powered hydroponic planting system consists of three major components: the solar power supply components, the hydroponic system components and the automation and monitoring components. The solar power supply components consist of a solar panel with a capacity of 80 watts, mounted on a 1-inch angle pipe frame. This connects to a lead-acid battery bank of 12V 60 Amp/Hr through a 12V MPPT charge controller that regulates the power and prevents the battery from overcharging. For safety, 12 AWG wire and a 10A fuse ensure safe power distribution throughout the system. The hydroponic system, powered by the solar system (Figure 1), consists of a 12V air pump to increase oxygen in the solution, thereby promoting root health, and a 12V water pump for nutrient circulation installed on the nutrient solution tank made from UV-resistant food-grade plastic. Within a 3-inch PVC pipe used as the growing tube, a float water level sensor determined the optimal water level required in the system. Furthermore, a NPK sensor with a power rating of 0.18W, operating temperature range of 5-45°C, and precision (± 0.1 accuracy), measured essential metrics such as Nitrogen, Phosphorous and Potassium and to condition the nutrient water based on the plants' need for optimal performance. The setup used four bulbs to provide artificial light when growing indoors or under the shaded systems, or when the sunlight is insufficient. At the heart of the automation and monitoring system is an Arduino Nano consisting of an ATmega328P microcontroller that reads sensors and controls the opto-isolated relays. It was paired with an ESP8266, 2.4GHz Wi-Fi module for wireless IoT data logging to the Thingspeak platform for real-time monitoring of NPK level in the nutrient water, water levels in the growing tube, and real-time control of pumps and lights. The isometric view of the developed system is presented in Figure 1.

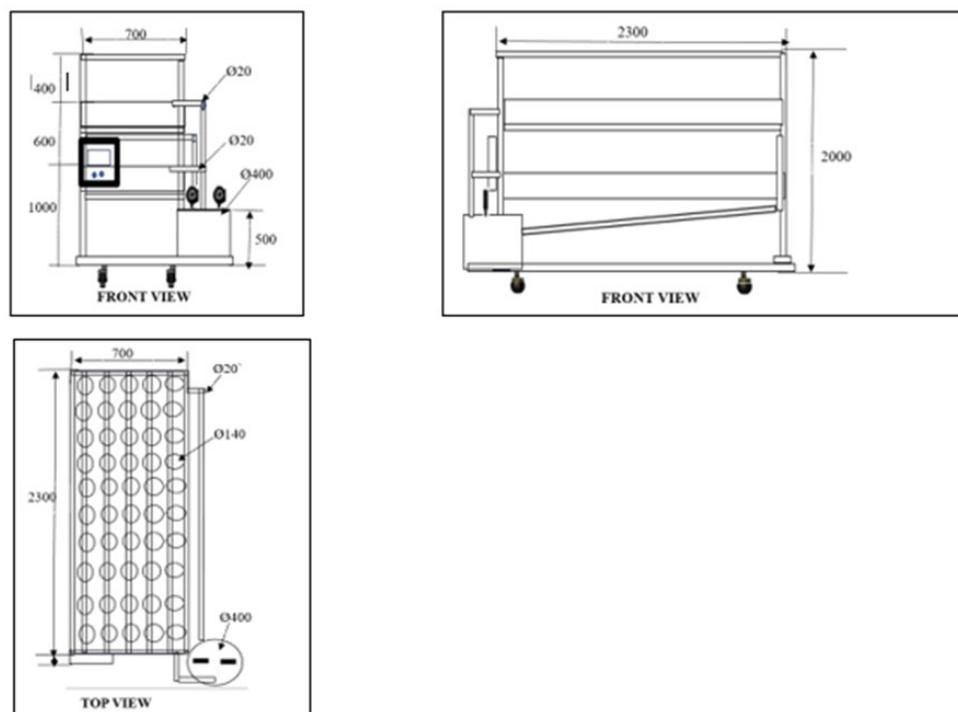


Figure 1. Isometric view of the developed system

2.2 Design Analysis

Determination of the Number of the Plant

The number of plants was determined as reported by [6] and is given as

$$N_{Pl} = N_p \times N_s \times N_h \quad (1)$$

where N_{Pl} is the number of plants, N_p is the number of pipes, N_s is the number of shelves, N_h is the number of plants holes

Determination of the quantity of nutrient solution required by the plant

The quantity of the nutrient required was determined as reported by [6] and is given as

$$Q_N = L_T + T_L \quad (2)$$

$$T_L = L_T \times \frac{L}{100} \quad (3)$$

where Q_N is the quantity of the nutrient required, L_T is the liters required, T_L is the total loss, L is the losses of water due to the consumption of plants and water evaporation from heat,

Determination of the inner dimensions of the container

The container is expected to hold 50 liters of water; therefore, the volume of the container was determined by assuming it is a rectangular container with a length and width of 35 cm and 45 cm, respectively. The height of the container was obtained as follows:

$$V = L \times B \times H \quad (4)$$

$$H = \frac{V}{B \times L} \quad (5)$$

where V is the volume of the container (cm^3), L is the length of the container (cm), B is the width of the container (cm), H is the height the container (cm)

Determination of the head of water inside the container

The head of water inside the container was determined as

$$H_w = \frac{L_w \times 1000}{L \times W} \quad (6)$$

where H_w is the head of water inside the container (cm), L_w is the liters of water, L is the length of the container (cm), and W is the width of the container (cm)

Design of the Pump

The total gallon of water per hour (GPH) of water that the pump needs to supply to the system every hour was calculated as reported by [6]

$$GPH = N_p \times f + L_{eff} \quad (7)$$

where GPH is the total gallons of water per hour of water that the pump needs to supply to the system every hour (Lit/h), N_p is the number of pipes, f is the flow rate (GPH), L_{eff} is the water losses (%)

Determination of the Total Power Required

The total power was determined as reported by [11] and is given as

$$P_T = P_{NS} + P_A + P_{AP} + P_{WP} + P_{ESP} + P_B \quad (8)$$

where P_T is the total power required (W), P_{NS} is the power required by 3-in-1 Sensor (NPK sensor) (W), P_A is the power required by the Arduino Nano (W), P_{AP} is the power required by the air pump (W), P_{WP} is the power

required by the water pump (W), P_{ESP} is the power required by ESP8266 (W), P_B is the power required by the bulbs (W),

Determination of the Daily Energy Requirement

The daily energy required was determined as reported by [11] and is given as

$$E_R = P_T \times t \quad (9)$$

where E_R is the total energy (W), t is the time (h), assume 2 days of backup and 30% loss.

Determination of the Battery Capacity

The battery capacity was obtained as reported by [12] as follows;

$$C_b = \frac{E_{total}}{V} \quad (10)$$

where C_b is the battery capacity (Ah), E_{total} is the total energy (W), V is the battery voltage(V)

Determination of the Solar Panel Size and Quantity

The required solar input per day was determined as reported by [13] by assuming five peak sun hours per day (common standard in Nigeria).

$$S_{Ir} = \frac{D_L}{S_h \times E_{ff}} \quad (11)$$

where S_{Ir} is the solar input required (W), D_L is the daily load (W), S_h is the sun hours (h), E_{ff} is the efficiency (%)

2.2 The Mode of Operation of the System

A charge controller stores the regulated electricity generated from the solar panel in a battery. The batteries powered the lights, sensors, automation, and water pump. The microcontroller automatically modifies the state of the pump and lights as required, after reading the sensor's data. The online Thingspeak platform notifies users of updates and alarms. To achieve this, the microcontroller (Arduino Nano) reads all sensor data and sends it to the ESP8266 Wi-Fi module, that uploads it to the Thingspeak platform. If the water level drops below the predetermined level, the microcontroller instructs the water pump to turn on to compensate for the shortage. The uploaded nutrient levels of the water make the user aware when more nutrients are required. In other words, when a reduction in the concentration of nutrients is sensed, the controller instructs the salt pump to compensate for the salt loss through a particular concentration from the second tank. The developed automated solar power hydroponic system along with its block diagram automatic is shown in Figures 2 and 3, respectively.

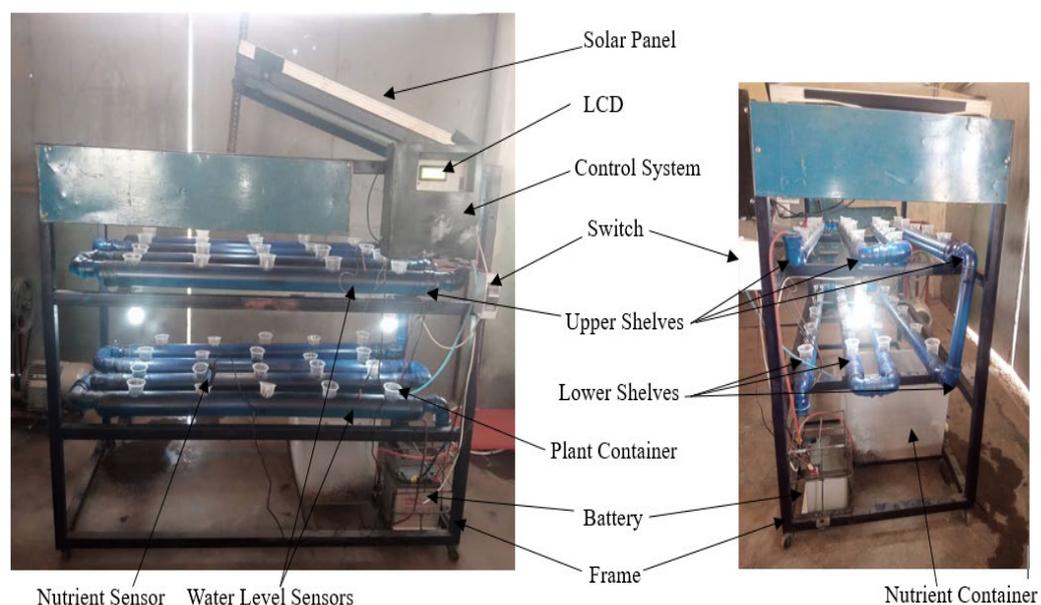


Figure 2: The developed automated solar power hydroponic system

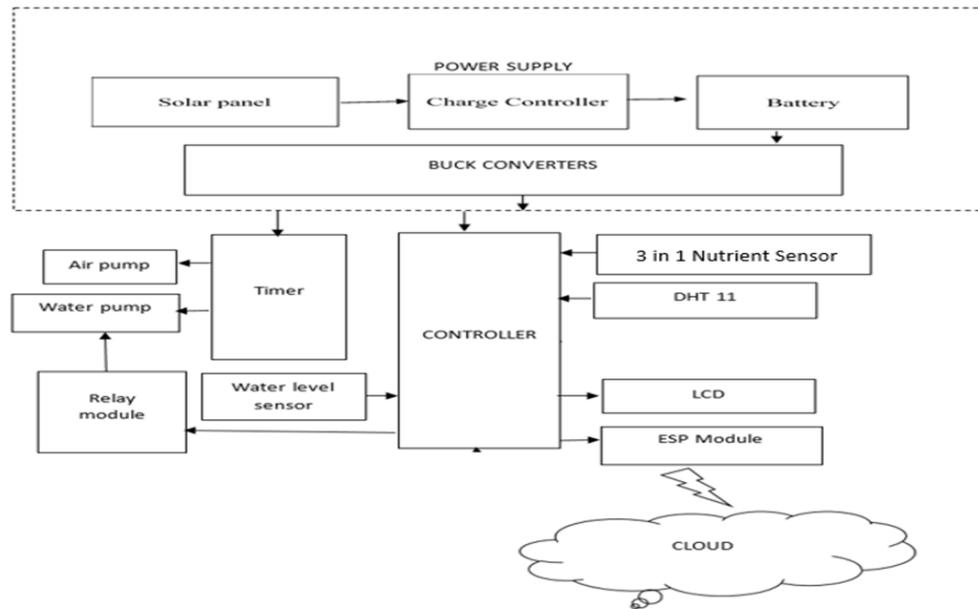


Figure 3: A block diagram of the automatic solar powered hydroponic system.

2.3 Testing and Validation

The various sensors used in the design had to be calibrated before using them. The overall circuit diagram of the system is shown in Figure 3, which presents all the sensors and the DC appliances connected with each other along the connection of the controller. The type of Arduinos used was Arduino Nano, which sends data to the ESP8266 Wi-Fi through serial communication.

2.4 Testing of Sensors

The NPK sensor was calibrated with reference nutrient solutions, which are provided with fixed N, P and K quantities. Three-point calibrations were performed for the individual nutrients, and calibration coefficients were modified if these departures were noted. The stability of the sensor was determined by immersing the probe in a steady solution over 24 hours, whereas cross-interference was measured after exposure to increasing concentrations of individual nutrients. The sensor was connected to a hydroponic control system to test its calibration and operational stability. The water level sensor is calibrated through testing; the reservoir is filled to specific reference points following manual measurement [14] [15]. The circuit diagram is shown in Figure 4.

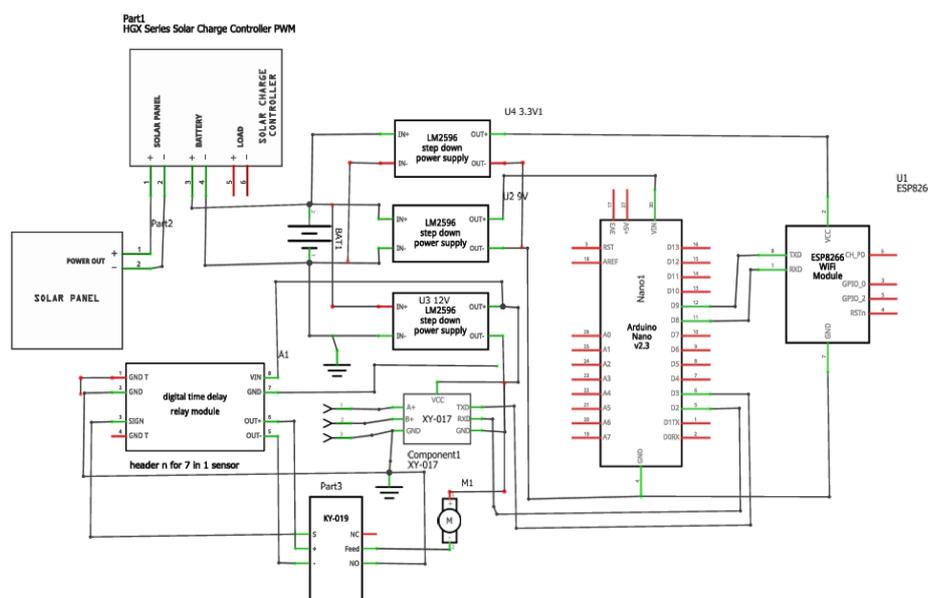


Figure 4: The Circuit Diagram of the Developed Automated Solar Power Hydroponic

3.0 Results and Discussion

3.1 Results

The system was successfully developed and tested; the results of testing are presented in Table 1. The operational and correct sequential functioning of the system is confirmed by initial zero readings. This reflects an appropriate system initialisation [16]. However, the level of the phosphorus increased gradually from 34 to 37 ppm. The concentration of nitrogen changed from 100 to 130 ppm but is higher than the 80 to 120 ppm reported by [17] for seedlings. Potassium also remained steady between 168 and 173 ppm, with these ranges being in accordance with [18] suggestion that optimal plant potassium levels range from 150 to 250 ppm. The water level 1 increased gradually from 193 to 650 units prior to the initiation of water level 2, indicating the designed hydraulic order.

Table 1: Result of testing of the systems

Time (hr)	Phosphorous (ppm)	Nitrogen (ppm)	Potassium (ppm)	Water level 1 (mm)	Water Level 2 (mm)
0	0	0	0	0	0
12:44	34	100	168	193	0
12:46	35	110	171	237	0
12:48	36	120	172	288	0
12:50	37	130	173	655	0
15:00	0	0	0	0	650

3.2 Discussion

The monitored nutrient concentration trends confirm that the automated dosing system is working as intended; see Figure 5. Over time the phosphorus concentration rose from 34 to 37 ppm, also showing that the controlled solution supplies were in the range suggested for vegetative growth by [19]; phosphorus levels at or below 10 ppm often indicate a limiting condition, indicating that the plants may not grow well. The range of 10 to 30 ppm – moderately adequate but not optimum for growers. The ideal for healthy vegetative growth is between 30 and 50 ppm. Levels of 50 to 80 ppm are quite high, however, and are still within a reasonable range for most plants. However, in contrast to [20] which reported an increase in the phosphorus uptake rate by 5 ppm/hour under certain conditions.

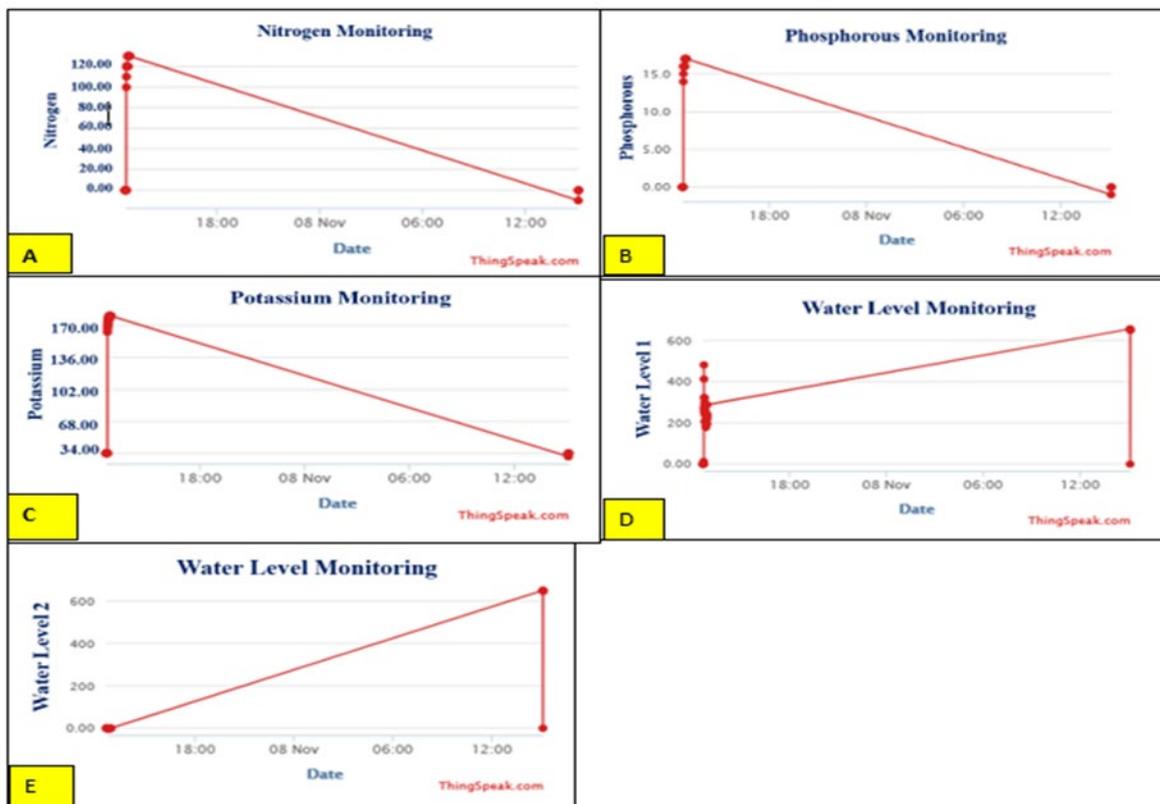


Figure 5: Sample graphs of the Thingspeak Web-interface of IoT platform: (A) Nitrogen, (B) Phosphorous, (C) Potassium, (D) Water level 1, (E) Water level 2 monitoring.

Nitrogen level, however, sharply increased by a 3-ppm leap in 6 min from 10 ppm to 13 ppm. This aligns with the report of [21], which states that the ideal rate of nitrogen uptake ranges between 2 and 5 ppm per hour under controlled conditions. The sequential water filling mechanism operated as designed. The delayed response of Water Level 2 was consistent with the hydraulic behavior outlined by [22]. Level 1 rapidly increases from 193 to 655 units within just six minutes, clearly indicating a high inflow rate or a system deliberately engineered to prioritize filling the upper layer first. During this period, Water Level 2 stays at zero until exactly 15:00—no movement whatsoever. This strongly suggests that a controlled release mechanism is in play, basically ensuring the lower layer does not get any water until the upper layer is filled to capacity. This approach aligns neatly with established hydraulic principles: layered systems typically focus on filling upper reservoirs first to stabilize pressure and manage flow effectively. Then, at precisely 15:00, Water Level 1 drops sharply to zero while Water Level 2 suddenly jumps to 650 units. This shift signals a transfer event, where water from the upper layer is released into the lower one, demonstrating a precise, intentional sequence consistent with controlled hydraulic operations. This finding aligns with the findings of [22].

4.0 Conclusion

The developed automated solar-powered NFT hydroponic system which integrate renewable energy and advanced agricultural technology, was successfully developed and tested. The system was powered by a solar panel of 80 W capacity and coupled to battery storage. By using IoT technology and automation with Arduino and ESP8266, the environment was accurately controlled without the need for manual operation. Furthermore, owing to the small footprint and vertical geometric confinement, it seems well-suited for urban areas and can replace regional food production in a sustainable manner. Considering current global challenges, the development of this system is essential for climate-smart agriculture.

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