INNOVATIVE ALGORITHMS FOR WATER AND SOIL MONITORING IN UAV-ASSISTED SOLAR PHOTOVOLTAIC IRRIGATION

Umaru, S.[1,2*], Mohammed, M.H.[1], Shekarau, R.A.[3], Mohammed, A.[3], Abubakar, A.S.[4], Adebomehin, A.A.[5], Yahuza, I.[6], Ibrahim, F.B.[7], Dangaji, A.S.[8], Lawal, M.S.[1], Dauda, M.[1,2], Momoh, M.O.[3], Munkaila, A.U.[9], Yahaya, U.O.[3], Dandago, K.K.[9], Zebedee, E.A.[9] and Isah, A.[6]

[1]Mechanical Engineering Department, Air Force Institute of Technology, Kaduna, Nigeria

[2]Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria

[3]Mechatronics Engineering Department, Air Force Institute of Technology, Kaduna, Nigeria

[4]Nigerian Airspace Management Agency, Abuja, Nigeria

[5]Mechanical Engineering Department, Air Force Institute of Technology, Kaduna, Nigeria

[6]Automotive Engineering Department, Air Force Institute of Technology, Kaduna, Nigeria

[7]Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria, Nigeria

[8]Kaduna State Agricultural Development Agency, Kaduna, Nigeria

[9]Aerospace Engineering Department, Air Force Institute of Technology, Kaduna, Nigeria

*Corresponding email: bnumar@yahoo.com

ABSTRACT

Precision agriculture has emerged as a transformative approach to address the growing challenges of food security, resource management, and environmental sustainability in agriculture. This study investigates the integration of cutting-edge technologies, including Unmanned Aerial Vehicles, Internet of Things (IoT) devices, and solar photovoltaic systems, to optimize water and soil monitoring in Unmanned Aerial Vehicles assisted precision agriculture. Unmanned Aerial Vehicles equipped with IoT sensors enable real-time data acquisition, facilitating precise interventions for crop health monitoring, irrigation management, and resource optimization. The development of innovative algorithms for spatiotemporal analysis further enhances the ability to interpret complex datasets, uncovering patterns critical for improving agricultural practices. Solar photovoltaic systems, tailored to the specific requirements of agricultural applications, provide a sustainable and cost-effective solution for powering water pumping and irrigation. By leveraging renewable energy sources, these systems reduce dependence on fossil fuels and grid electricity, aligning with global efforts toward sustainable energy use in agriculture. Despite their potential, the adoption of these technologies faces challenges such as high implementation costs, data management complexities, and scalability concerns, particularly for small-scale farmers. The study's findings demonstrate the feasibility and effectiveness of integrating these technologies to achieve optimal resource utilization, improved agricultural productivity, and reduced environmental impact. Addressing key barriers through collaborative efforts among researchers, policymakers, and industry stakeholders is essential to ensure the widespread adoption of these innovative approaches. This research underscores the transformative potential of technology-driven solutions in fostering sustainable and efficient farming practices, contributing significantly to global efforts to meet the growing demand for food while minimizing ecological footprints.

Keywords: Precision Agriculture, Unmanned Aerial Vehicles, Internet of Things, Solar Photovoltaic Systems, Sustainable Water Management

1 INTRODUCTION

Globally, the population has been increasing steadily over the years and it is expected to reach over 9 billion by 2050, with much of the growth occurring in developing regions, particularly Asia and Africa [1]. As the population increases, so does the demand for food and meeting the demand poses a significant challenge, especially considering issues such as loss of diversity, water scarcity, land degradation and climate change. To address the significant need for food due to population growth, agriculture must transform through the adoption of Information and Communication Technologies (ICT). Currently, the trending concept is precision agriculture (PA) which uses the most recent ICT techniques to cultivate food in an environmentally sustainable and efficient manner [2]. Also, PA involves utilizing extensive data sources alongside sophisticated artificial intelligence (AI) tools to assist farmers in making more precise and informed decisions towards ensuring optimal actions such as applying the right inputs at the right times and in the right locations. The overarching aim is to achieve both economic and environmental objectives [3]. ICT technologies such as Unmanned Aerial Vehicles, Remote Sensing and the Internet of Things (IoTs) are efficiently employed for agricultural practices [4]. Precision Agriculture (PA) is an advanced farming approach that utilizes various technologies to optimize crop yield and resource efficiency. It employs tools such as GPS, remote sensing, and GIS to monitor and respond to field variability [5]. PA addresses challenges like soil degradation, climate variation, and increasing costs by leveraging Wireless Sensor Networks, Machine Learning, and Artificial Intelligence [6]. The integration of emerging technologies, including fog/edge computing, Software Defined Networks, and nanotechnology, is transforming PA practices [6] This approach offers numerous benefits, including reduced food losses and improved profitability [7]. However, implementing PA systems also presents challenges that need to be addressed [8]. As global food demand rises, PA represents a promising solution to enhance agricultural productivity while minimizing resource inputs and environmental impact [8, 5]. Precision agriculture has emerged as a pivotal approach in addressing the contemporary challenges facing global agriculture. As the world grapples with the need to produce more food to feed a growing population, there is a simultaneous demand for sustainable practices that minimize environmental impact. One critical aspect of agricultural sustainability revolves around efficient water management, particularly in the context of precision agriculture where precision technologies are deployed to optimize resource utilization. IoTs framework presents a new and fresh approach to precision agriculture which facilitates the immediate and location-specific oversight of cultivated fields. Within IoT-driven precision agriculture, a comprehensive system is used to supervise crops, aiming to automate various key farming tasks including disease detection, fertilizer application, irrigation, and growth monitoring. In this framework, it plays a crucial role in gathering real-time data from agricultural fields which are then analysed and utilized to make essential decisions concerning crop management [9]. However, IoT devices generate massive amounts of data produced in real-time, leading to data and information overload for users and the systems. Processing, analysing, and deriving actionable insights from large-scale IoT data streams require robust data management and analytics capabilities. Remote sensing (RS) stands out as a pivotal technology in precision agriculture and has been widely recognized for its effectiveness in monitoring cultivated fields, contributing significantly to precision agriculture for over three and a half decades [10]. It primarily relies on satellite images obtained from manned aircraft to monitor the status of vegetation during specific growth stages. However, since it depends on the satellite, the frequency of satellite images may be limited due to factors like cloud cover, satellite revisit times and many others. This limited spatial resolution can restrict the ability to monitor changes in crop conditions or several other environmental factors with high frequency leading to potential missing critical events [9]. Also, using RS technology such as drone-based sensors or satellite imagery often results in high costs for equipment, data acquisition and analysis software. Despite these challenges, advancements in AI, cloud computing, and affordable drone technology are helping to overcome some limitations, making RS increasingly viable for rice irrigation management. However, ensuring affordability, accessibility, and proper training is crucial for its broader adoption in agriculture.

2 LITERATURE REVIEW

This literature review provides a comprehensive understanding of the current state of solar PV applications in agriculture, the intricacies of water pumping in agricultural settings, the role of precision agriculture technologies, and the existing gaps and challenges.

2.1 Solar Photovoltaic Technology in Agriculture

Agrivoltaic systems, which combine solar photovoltaic (PV) energy generation with agricultural production, offer a promising solution to land-use conflicts and increasing energy demands [11]. These systems can generate renewable energy without significantly impacting crop yields, as demonstrated in a grape cultivation study [12]. However, optimal design is crucial, as panel configuration can affect both energy and agricultural production [11]. Farmers' perspectives on agrivoltaics reveal potential benefits but also concerns about long-term land productivity, market potential, and system flexibility [13]. Solar PV water pumping systems for irrigation present an attractive alternative to grid power in rural areas, offering significant returns on investment and reduced carbon footprints [14]. As agrivoltaic technology continues to evolve, further research and optimization models are needed to maximize both crop yields and energy production while addressing farmers' concerns [11, 13]. Solar photovoltaic water pumping systems (SPVWPS) are emerging as sustainable solutions for agricultural irrigation, addressing challenges of fossil fuel dependence and electricity availability in rural areas [14, 15]. These systems typically comprise PV arrays, charge controllers, batteries, and DC or AC pumps, with capacities ranging from small-scale 40W setups to larger 4-5.5kW installations [14, 16]. SPVWPS design and simulation tools like PV system enable performance analysis under varying environmental conditions, optimizing system efficiency [15, 17]. Implementation of SPVWPS offers numerous benefits, including reduced carbon footprint, low maintenance costs, and long product life [14, 17]. Government incentives, such as India's KUSUM scheme, further promote SPVWPS adoption, potentially yielding significant returns on investment for farmers over the system's lifetime [14.

2.2 Water Pumping in Agriculture

Water pumping is a critical aspect of agricultural operations, influencing crop yields and overall farm productivity. Traditional water pumping systems, often reliant on non-renewable energy sources, contribute to environmental degradation and operational costs. Solar photovoltaic water pumping systems (SPV-WPS) are emerging as a sustainable alternative to grid-powered irrigation in agriculture. These systems can be precisely sized using synthetic daily rainfall and irrigation data to meet crop water needs with high reliability [18]. Optimal control strategies can minimize operational costs by maximizing PV utilization and reducing grid dependence, potentially reducing energy costs by 44.4% [19]. SPV-WPS offer significant economic benefits, with farmers potentially gaining a minimum 250% return on investment over a 25-year project lifetime [14]. However, system performance is influenced by factors such as total system head and solar radiation, with higher system heads reducing efficiency and higher solar radiation improving performance [20]. Overall, SPV-WPS present a promising solution for sustainable agricultural water pumping, offering both economic and environmental advantages over fossil fuel-powered alternatives.

2.3 Unmanned Aerial Vehicles (UAVs) in Agriculture

Recently, UAVs have emerged as highly valuable agricultural tools, mainly in ground-sensing applications within the realm of smart farming. Initially, UAVs were developed for military purposes, later it was adapted for various civilian applications such as recreational purposes, policing, agriculture and many others [21]. UAV serves as a mobile hotspot in areas where communication networks are lacking, hence, it’s often used in gathering soil and crop data to monitor and regulate precision water management systems. The Unmanned Aerial Vehicles (UAVs) had the ability to transform the conventional remote sensing platforms for immediate crop monitoring, weed identification, detection of diseases, estimation of yield and the implementation of diverse pest and nutrient management approaches [22]. In agriculture, the preferred choice is a UAV equipped with a blend of IoT sensors. These sensors can detect soil temperature and

moisture, transmitting this information to farmers via the UAV. As a result, pinpointing areas affected by droughts, water shortages, and soil dryness is made effortless. It assists the farmers in implementing precautionary measures like "contouring, damming, draining the surface water, and curtailing for further irrigation" [23]. Despite the numerous advantages, UAV-mounted Internet of Things devices are dependent on internal power sources, including batteries, which have a certain amount of capacity and durability. To maintain the maximum performance of IoT devices and avoid prematurely depleting the UAV's battery, which might result in shortened flight lengths and mission durations, power consumption considerations are essential. Also, integrating IoT devices onto UAV platforms may increase the overall cost of UAV systems including procurement, customization, maintenance, and operational expenses [23].

2.4 Precision Agriculture and Water Management

Precision agriculture, characterized by the use of technology for precise resource allocation, has become integral to modern farming practices. Precision agriculture techniques offer significant potential for improving water management in farming systems. Recent studies have explored various approaches, including closed-loop control irrigation systems based on soil moisture measurements [24] and the use of soil and plant sensors, satellite imagery, and GIS for site-specific management [25]. Accurate estimation of evapotranspiration is crucial for efficient water use, with advanced technologies like remote sensing and machine learning algorithms enhancing accuracy [26]. Implementation of ICT-based decision support systems for precision irrigation management has shown promising results in reducing water consumption. For instance, a system called DSSPIM demonstrated the ability to detect inefficiencies in irrigation water use and potentially reduce water consumption by 20% through controlled deficit irrigation strategies [27]. These advancements in precision agriculture contribute to more sustainable and efficient water management practices in farming. Integrating solar PV energy systems into precision agriculture aligns with the broader goal of developing smart and sustainable farming practices. In summary, the literature review establishes the context for this study by highlighting the current state of solar PV technology, Water pumping in agriculture, Unmanned Aerial Vehicles (UAVs) in Agriculture and the role of precision agriculture in sustainable water management. Identifying gaps and challenges in existing knowledge provides a foundation for the subsequent sections of this paper, where we present our methodology.

3 METHODOLOGY

This study focuses on the development of advanced technologies, including cost-effective Unmanned Aerial Vehicles (UAVs) and wireless sensor networks, for comprehensive water and soil monitoring in precision agriculture. A novel algorithm for assessing water availability and soil quality was developed, leveraging data collected from UAV-mounted sensors. The research integrates state-of-the-art computational techniques from artificial intelligence (AI), including deep learning, machine learning, and optimization strategies, specifically tailored for UAV-assisted agricultural monitoring. By incorporating AI-driven data analytics, this approach enables a more detailed and accurate assessment of soil moisture levels and water distribution, surpassing the capabilities of conventional monitoring methods. The data processing framework is designed to handle high-dimensional datasets efficiently, utilizing advanced feature extraction and pattern recognition techniques. Novel computational models, aligned with established standards such as IEEE 1451 for smart sensor interfaces and ISO 11074 for soil quality assessment, facilitate accurate data acquisition and interpretation. Spatiotemporal analysis techniques are employed to examine the dynamic interactions between soil and water over time. By integrating both spatial and temporal dimensions, the system identifies trends and patterns that enhance resource management and optimize agricultural practices. Furthermore, Internet of Things (IoT) sensor data is fused with UAV-derived imagery to provide a holistic representation of agricultural conditions, supporting real-time monitoring and data-driven decision-making. This research addresses key challenges in precision agriculture, including resource allocation, crop health monitoring, and environmental sustainability. By adhering to industry standards such as ISO 22000 for food safety management and IEEE P1936.1 for agricultural robotics, the proposed methodology ensures reliability, scalability, and interoperability with existing agricultural technologies. The findings contribute to the advancement of sustainable farming

practices by enabling precise and efficient resource utilization through UAV-assisted AI-driven monitoring systems.

3.1 Development of low-cost Unmanned Aerial Vehicles

The development of unmanned aerial vehicles (UAVs) for precision agriculture begins with the conceptual design of the airframe, propulsion system, and control mechanisms using computer-aided design (CAD) software, following established aerospace engineering practices [28]. The fabrication of prototype components was carried out using CNC machining and additive manufacturing (3D printing), ensuring compliance with industry tolerances and material strength specifications [29]. These components were then assembled into a fully functional UAV prototype. An initial experimental evaluation was conducted to assess the aerodynamic performance, weight distribution, and structural integrity of the prototype, following standard testing methodologies [30]. Various sensors, as detailed in Table 1, were mounted on the UAV, followed by precise calibration and alignment to ensure accurate data acquisition, based on IEEE sensor standards [31]. The UAV's avionics suite—including flight control systems (accelerometers, gyroscopes, and autopilots), power distribution components (voltage regulators, batteries), and communication modules (telemetry systems, remote control)—was carefully selected and integrated in accordance with recommended UAV operation guidelines [32]. Additionally, flight control software and sensor data acquisition systems were developed and configured to enable autonomous and controlled flight, leveraging methodologies from embedded systems and UAV automation research [33]. Finally, a comprehensive ground test was conducted to verify the functionality and interoperability of hardware and software components, ensuring operational reliability before deployment in precision agriculture applications.

3.2 System Requirements and Design Criteria

The subsequent phase involves a comprehensive evaluation of the water demand for the selected crops, taking into account key agronomic and environmental factors, including soil texture and structure, regional climatic conditions, and specific crop water requirements as outlined in the FAO Irrigation and Drainage Paper No. 56 [34]. This assessment is critical for defining the technical specifications of the solar photovoltaic (PV)-powered irrigation system. The system design is guided by parameters such as the required water flow rate, daily energy consumption, and peak irrigation demands, ensuring that energy generation aligns with periods of maximum water requirement [35]. Furthermore, the integration of solar-powered irrigation must comply with international standards such as IEC 62253:2011, which provides guidelines for the design and performance assessment of photovoltaic pumping systems [36].

Step 1: Determination of Water Requirements

Rice typically requires consistent moisture throughout its growth stages. The water requirement depends on factors such as soil type, climate, and stage of growth. As a general guideline, rice fields may require a depth of water ranging from 5 to 15 centimetres during the growing season. In lowland rice cultivation, transplanted rice on puddled soil requires a consistent layer of 5–10 cm of standing water on the soil surface [37]. At the beginning, when rice was transplanted, the crop water need was only 0.87mm/day (June), but it gradually increased and reached to 15.95mm/day [38].

Step 2: Calculate Water Volume

Assuming a conservative estimate of 10 cm water depth for the entire 50m x 50m plot: Total water volume = Area × Depth.

3.3 Solar PV System Design

The design of a solar photovoltaic (PV) water pumping system involves the careful selection of system components, including solar panels, pumps, and other critical elements to ensure optimal performance and efficiency. According to IEC 62548 [39] proper system design must account for electrical safety, environmental conditions, and mechanical stability. Standards such as IEC 61724-1 [40] guide performance evaluation and long-term monitoring to ensure reliability. Furthermore, the system design

integrates essential safety measures and redundancies to maintain reliable and uninterrupted water pumping operations. The inclusion of protection mechanisms, as outlined in IEC 60364-7-712 [41] ensures compliance with industry best practices. These measures help mitigate risks associated with voltage fluctuations, shading effects, and mechanical failures, ultimately enhancing system resilience and operational continuity [42].

3.3.1 System Sizing, Solar Panel Selection and Configuration

The selection of solar panels for agricultural applications requires a comprehensive evaluation of efficiency, durability, and compatibility with field conditions. In this study, high-efficiency monocrystalline silicon solar panels were chosen due to their superior performance metrics, including high power conversion efficiency (typically above 20%) and enhanced durability in outdoor environments [43]. Monocrystalline panels have been demonstrated to perform well under varying environmental conditions, making them suitable for precision agriculture applications where consistent energy output is required [44]. To ensure system reliability, the selected panels were evaluated for resistance to environmental stressors such as dust accumulation, debris impact, and occasional extreme weather conditions, in accordance with IEC 61701 [45] for salt mist corrosion resistance and IEC 62716 [46] for ammonia resistance-both critical in agricultural settings. The sizing of the photovoltaic (PV) system was determined based on the peak power demand of the water pumping system, daily irrigation water requirements, and seasonal variations in solar insolation [47]. A total of eight monocrystalline solar panels, each rated at 300 W, were configured to maximize energy capture throughout the day. The panel tilt and orientation were optimized based on the site's geographic latitude, following standard methodologies outlined in [48. 49]. The optimization aimed to enhance photovoltaic performance by aligning the array with the solar declination angle and minimizing shading losses, thereby improving overall energy yield and system efficiency [50].

3.3.2 Solar PV Sizing

Energy required per day: 12.24 kWh. Considering 5 kWh/m²/day solar irradiance and system efficiency of 70%: Required PV capacity = 12.24 kWh/day/5kWh/m^2×0.7 ≈ 2.45 kW.

3.3.3 Inverter and Battery System

To ensure a continuous and reliable power supply, an inverter and battery system were integrated into the design.

3.4 Water Pump Selection

The water pump selection process considered the specific water requirements of the crops, the elevation lift, and the variability in demand over time. A SP 9-11 solar-powered water pump was chosen for its energy efficiency and compatibility with the solar PV system. The pump's capacity was aligned with the agricultural water demand, and its design allowed for easy integration with the solar energy supply. This is the detail of choosing a submersible pump capable of lifting water from 20 meters and delivering the required flow rate involves several key steps. Determining Required Flow Rate and Total Dynamic Head (TDH). Flow Rate (Q): Flow Rate (Q) = 250/24 = 10.4 m^3/hour. Flow Rate (Q): Flow Rate (Q) = 250/24 = 10.4 m3/hour. Total Dynamic Head (TDH): Static Head: The vertical distance the water needs to be lifted. In this case, it's 20 meters. Friction Losses: Losses due to friction in the pipes, typically around 10% of the static head for a simple system. Assuming 2 meters. Pressure Requirement for Sprinklers: Sprinkler systems typically require around 2-3 bars of pressure (1 bar ≈ 10 meters of head from P = ρgH). Assuming 2.5 bars, which is 25 meters. Total Dynamic Head (TDH): TDH = 20 m (static head) +2 m (friction losses) +25 m (sprinkler pressure) = 47 meters.

3.5 Evaluate Site Conditions

On average, the solar irradiance at Kaduna ranges from 5.19 to 6.17 kWh/m^2/day [51]. Solar irradiance (kWh/m²/day) at the site is 5.19 to 6.17 kWh/m^2/day and the source of water is borehole with a depth of the water table for submersible pump placement of 20 metres.

3.6 Control System and Sensors

The implementation of an intelligent control system significantly enhanced the efficiency of water pump operations by leveraging real-time data for optimized irrigation management. Soil moisture sensors, strategically deployed across the field, continuously monitored moisture levels, providing critical input to the control system. This system, integrating microcontrollers and programmable logic controllers (PLCs), dynamically adjusted pump operations to align with crop water requirements while minimizing energy consumption. The approach aligns with precision irrigation principles outlined in the ISO 11783-10 standard for agricultural electronic control systems [52] and supports sustainable water management practices as recommended by the Food and Agriculture Organization [53]. Furthermore, similar automation strategies have demonstrated substantial water savings and improved crop yield in previous studies [54, 55].

4 RESULTS AND DISCUSSION

4.1 low-cost Unmanned Aerial Vehicles (UAVs)

Table 1 describe the UAV components developed.

Table 1. Description of the UAV components

Components	**Functions**
Constructing the Airframe	
Locally developed carbon fibre composites	The carbon fibre is used for building the fuselage and the wings
Aluminium alloy sources from scrap sites	Aluminium alloy is utilized for structural components such as motor mounts, landing gear and frame supports
Foam core covered with composite materials	For wing cores and many other aerodynamic surfaces
Electronics integration	
Printed circuit boards (PCBs)	Made from flexible materials or fibre glass-reinforced epoxy laminates for mounting electronic components like communication modules, sensors and microcontrollers
Copper wire	For wire connections between actuators, power sources and electronic components
Propulsion and power	
Electric motors	Provide thrust for flight and also power the UAV propulsion system
Lithium Polymer (LiPo) Batteries	It supplies power to the electronic systems in the UAVs
Sensors and payload	
Multispectral/Hyperspectral cameras	Utilized for environmental mapping, vegetation analysis and crop monitoring
Soil moisture sensors	To measure soil moisture content while also giving data for irrigation management
Miscellaneous include • rivets, bolts, nuts and screws for securing the connection • Sealing joints, bonding component for providing waterproofing	

4.2 System Requirements

At the beginning, when rice was transplanted, the crop water need was only 0.87mm/day (June), but it gradually increased and reached to 15.95mm/day [38]. Total water volume = 50m × 50m × 0.1m = **250 cubic meters.** Water required per day = 10cm/day × 2500 m^2 = 250/24 = 10.4 m^3/hour.

4.3 Solar PV System Design

Number of 300W panels: Number of panels = 2.45 kW/0.3 kW = 8.16 ≈ 8 panels.

4.4 Pump Specifications

i. Pump Flow Rate: The pump should handle at least 10.4 m^3/hour.

ii. Pump Head: The pump must provide a head of at least 47 meters. Verify Power Requirements and Efficiency.

Pump Efficiency: Ensure the pump operates efficiently at the required head and flow rate. Typical efficiencies range from 60% to 75%.

Power Calculation: Using the formula $P = (Q \times H)/(367 \times \eta)$. $P = (10.4\ m^3/hr \times 47\ m)/(367 \times 0.653) \approx 2.04$ kW. Daily energy consumption: Energy = 2.04 kW×6 hours = 12.24 kWh/day.

4.6 Control Unit

Figure 1 is the picture of the smart irrigation control Unit developed showing the different indicators and buttons of the unit.

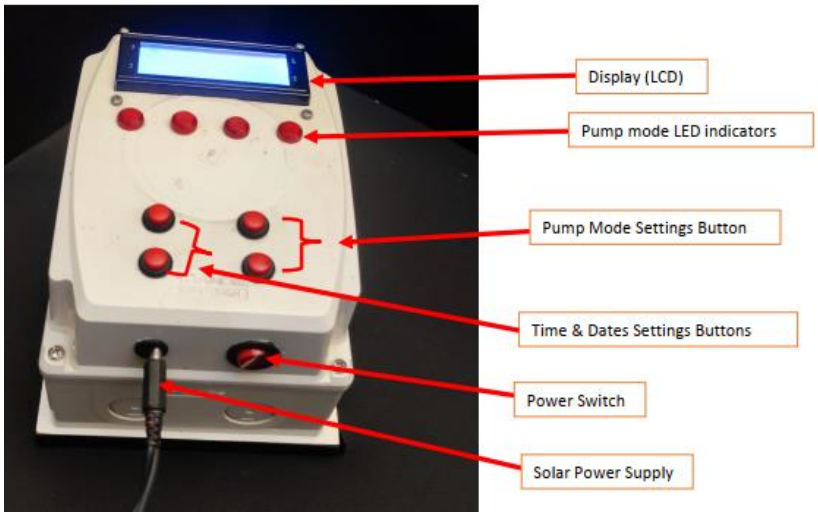

Figure 1. Smart Irrigation Control Unit

4 CONCLUSIONS

Precision agriculture transforms farming by utilizing advanced technologies to enhance food security, sustainability, and resource efficiency. This study examines the integration of UAVs, IoT devices, and solar PV systems to optimize water and soil monitoring, improving productivity while minimizing environmental impact. UAVs provide high-resolution, real-time data for crop and soil analysis, enabling precise interventions like targeted irrigation. However, high costs limit accessibility, particularly for small-scale farmers. Similarly, IoT frameworks revolutionize farming by enabling real-time resource management, though challenges in data processing persist. AI-driven analytics could enhance insights from large datasets. Solar PV systems offer a renewable energy solution for irrigation, reducing reliance on fossil fuels. Addressing system optimization and environmental factors can further enhance sustainability. The study's AI-driven algorithms improve soil and water monitoring, optimizing resource use. In conclusion, integrating UAVs, IoT, and solar PV systems offers a comprehensive approach to agricultural challenges. Overcoming financial, data management, and scalability barriers through collaboration among researchers, policymakers, and industry leaders will be crucial in ensuring precision agriculture's global adoption.

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