Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 33 No. 1s (2026)

Design of an IoT-Enabled PLC Framework for Efficient Water Management and Crop Optimization in Agrivoltaic Systems

Dr. Alugonda Rajani[1]

Assistant Professor, Department Of ECE, JNTUK.

rajani.alugonda@jntucek.ac.in[1]

Bandaru Anuhya[2]

Scholar, JNTUK

abhinay14311@gmail.com[2]

Article History:

Received:12-12-2025

Revised:05-01-2026

Accepted:18-02-2026

Abstract:

This studyintroduces a refined approach to farming with sunlight, combining solar panels and crop growth while using connected sensors through long-range wireless signals alongside wiring data transfer. Farming under solar arrays saves space by producing food and electricity together on shared ground. Still, current setups struggle due touneven water delivery, unstable power handling, weak links among devices, and outdated plant behavior predictions when weather shifts occur.

One wayaround these drawbacks begins with anewdesign:an IoT-based smartwater control setup paired with dynamic crop models. Instead of relying on extra wiring, power line communication moves data quickly using current electrical lines. For field sensors spread far apart, LoRaWAN handles connections efficiently - long reach, little power needed. Data flows nonstop - from earth dampness toweather shifts to plantstate - shapingsmarter watering plans. Health tracking for crops gets sharper. Energy use adjusts in response. Scaling up stays affordable.

A key part of the system lies in its ability to fine-tune fertilizers according to both soil conditions and how crops develop over time. Because nutrients are applied more precisely, yields rise -alongside better use of water - while excess runoff and ecological harm drop off. Testing via MATLAB models, together with real-world examples, confirms gains across farming output, smarter watering practices, and improved energyoperations. When combined, programmable logic controls, long-range wireless communication, and smart nutrient handling open doors - not just for growing food sustainably - but also for sharing land wisely between farming and clean power generation.

Keywords: Agrivoltaics systems, PLC, LoRa WAN- based IoT, smartwater management,dynamic crop modelling, sustainable energy, precision agriculture, Nutrient Optimization.

1. Introduction

Agri-voltaic systems (AVS) enhance land-use efficiency, renewable energy uptake, and agricultural sustainability by combining solar power generation with crop growth [1], [3], [5], [8], [10]. However, problems including inconsistent communication, inefficient water management, and energy optimization limit their effectiveness[6], [13], [14]. Conventional farming systems emphasis on strict, resource-intensive methods leads to uncertain agricultural output and reduced sustainability [10], [13].

Recent advancements in IoT, PLC, and LoRa WAN technologies offer effective solutions through real-time sensing, automated control, and data-driven decision-making [2], [6]. These clever systems enable precise irrigation management by continuously monitoring soil and environmental conditions, boosting agricultural productivity and resource efficiency [2].Beyond irrigation control, precision agriculture relies heavily on dynamic crop modeling, which makes use of machine learning algorithms to forecast crop growth, estimate yield, and assess environmental impacts [3], [8], [13].. Therefore, data-driven and adaptive crop modeling systems are required to improve prediction accuracy and resilience in changing agricultural settings [14].

Not with standing its benefits, a number of operational issues, most notably ineffective water management, subpar energy use, and poor coordination across intelligent farming components, are impeding the widespread use of agrivoltaics [6], [14]. Traditional irrigation methods frequently use manual management and static schedules, which results in excessive water use, uneven crop development, and uncertain yields [2], [10]. These drawbacks emphasize the need for data-driven, adaptable technology that can react quickly to crop and climatic circumstances [6].

Figure 1: Structure of Agrivoltaics

Developing an IoT-driven agri-voltaic system that integrates intelligent water management, adaptive crop modeling, and efficient energy usage is the aim of this project . Over the existing power infrastructure, the proposed system employs a PLC for high-speed data transfer and LoRa WAN for long-range, low-power communication amongst scattered sensors [6], [7]. AI-based techniques continuously collect and assess real-time environmental data to enhance crop health, boost irrigation effectiveness, and support informed decision-making [2], [4].

Adopting a hybrid communication architecture, LoRaWAN offers energy-efficient, long-range connection over dispersed agricultural fields, while PLC enables dependable, high-speed data transfer inside localized control networks [6], [7].. The methodology also includes dual-level water allocation optimization, which addresses both economic efficiency and fair water distribution. It also incorporates advanced photovoltaic performance analysis to align solar energy production with agricultural needs [5], [11].

As it directly affects crop development, yield quality, and environmental sustainability, effective nutrient management is a crucial part of precision agriculture [13], [14]. Nutrient optimization in contemporary agrivoltaics-based smart farming systems requires precise coordination with crop development phases, water availability, and energy resources to prevent overfertilization, nutrient loss, and soil deterioration [6], [10]. An integrated framework that facilitates intelligent nutrition optimization through automated control, data-driven decision-making, and real-time sensing is shown by the architecture seen in the image [2], [14].

Crop development stage monitoring and soil nutrient sensors are integrated into the suggested system to continually evaluate plant needs and nutrient availability. The nutrient optimization module processes these inputs and chooses the best manner, amount, and time to give nutrients. The technology maintains optimal nutrient absorption across several development phases while minimizing fertilizer waste by matching nutrient delivery with real crop needs [4], [12].

In this system, intelligent water management, irrigation control, and nutrient optimization are closely related. Fertigation techniques are synchronized with optimal irrigation schedules by the system since soil moisture conditions have a significant impact on nutrient absorption. Leaching losses are decreased, crop development is consistent throughout the field, and fertilizer utilization efficiency is increased using this coordinated method.

The nutrient optimization process is further strengthened by machine learning and analytical techniques, which examine both historical and current data on crop performance, soil conditions, and environmental variables. These models make it possible to provide dynamically adjusted nutrient recommendations in response to variations in crop growth patterns, soil fertility, and climate. Nutrient application techniques are improved by experimental validation modules in the design, which guarantee precision and dependability in practical settings.

Furthermore, smooth data sharing between sensors, controllers, and cloud-based platforms is made possible by the incorporation of IoT communication technologies. By minimizing manual involvement and increasing operational efficiency, automated fertilizer tanks and nutrient valves are managed based on optimal judgments. The technology maximizes crop output while promoting sustainable farming methods by fusing nutrient optimization with agrivoltaics infrastructure powered by renewable energy.

The effectiveness of the proposed system is validated by realistic case evaluations and simulated studies, with a focus on key performance indicators including irrigation efficiency, resource consumption, and agricultural output improvement. An overview of the primary contributions of this study is provided below:

1. The development of an Internet of Things-enabled intelligent water management system that enhances irrigation efficiency and conserves water by utilizing real-time sensor data and AI-driven analytics.
2. Using both historical and present data, a dynamic crop modeling system based on machine learning is implemented to enable adaptive agricultural decision-making.
3. The combination of PLC and LoRaWAN technologies to provide an energy-efficient, scalable, and cost-effective precision agricultural communication infrastructure.

4. The development of an architecture for hybrid communication that combines quick PLC data transmission with long-range LoRaWAN connections.
5. To verify the proposed framework and demonstrate how agrivoltaic systems improve agricultural productivity, energy efficiency, and sustainability in general, simulation and case-study analysis are employed.

2. Objectives

This project focuses on creating a smart Agri-Voltaic setup by combining IoT, PLC, and LoRaWAN to improve farming accuracy alongside efficient energy use. Rather than relying on traditional methods, it builds a responsive watering model that tracks soil dampness along with surrounding conditions - adjusting irrigation timing while reducing excess water use automatically.

A key aim involves building a steady, low-energy mix of Power Line Communication and LoRaWAN systems so signals stay strong over wide farming zones. Instead of relying on one method alone, merging these channels helps maintain consistent data flow under shifting field conditions.

Because environments change unpredictably, using both past trends and live inputs allows models to adjust crop forecasts dynamically. While technology handles connectivity, the insights feed into smarter choices when weather patterns shift suddenly.

Starting differently each time, the setup works toward building a tool to manage nutrients by adjusting fertilizer according to what the soil holds and how crops develop, which helps increase harvest while limiting wasted inputs. Solar energy gets fine-tuned too, matching sun-powered output with when water pumping and machinery need power across fields.

Taken together, gains emerge - not just in output but in smarter use of materials and lasting farming balance - through these linked improvements.

3.Methods

3.1 Existing Method

Smart agriculture might be advanced by integrating programmable logic controllers (PLCs) with Internet of Things (IoT) technology in agrivoltaic systems, but there are still a number of operational and technological obstacles to overcome. Conventional irrigation techniques are the mainstay of current agrivoltaics water management strategies, which frequently lead to excessive water use, unequal distribution, and irregular crop output. When real-time adaptation is restricted in large-scale deployments, these inefficiencies become more noticeable.

Many of the crop modeling techniques used today rely on static characteristics and historical data, which has serious constraints as well. Climate fluctuation, soil heterogeneity, and shifting microclimates brought on by photovoltaic shadowing are examples of dynamic environmental circumstances that such models find difficult to adjust to. This often leads to a tradeoff in the efficacy of decision-making and the accuracy of yield forecast.

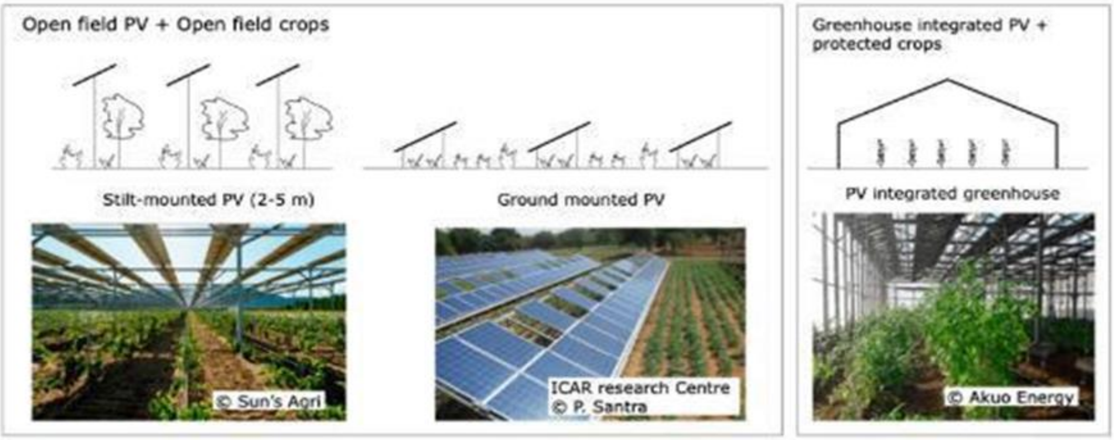

Figure 2: Structure of AgriVoltaic Systems

In scalable agrivoltaics applications, communication between dispersed sensors and centralized control systems is still another significant obstacle. Although PLCs provide quick processing and dependable local control, they are not built for long-distance communication over large agricultural fields. On the other hand, LoRaWAN offers long-distance, energy-efficient connection; but, in order to guarantee data synchronization, system resilience, and dependability, it must be carefully integrated with PLC-based systems. Automation, scalability, and real-time responsiveness may be hampered by inadequate coordination across these technologies.

The design of agrivoltaic systems is made more difficult by energy management as photovoltaic generation needs to be efficiently synchronized with sensor functioning, control infrastructure, and irrigation demands. Numerous current systems focus on energy management, crop modeling, or water management separately; they don't have a single framework that optimizes all three at once.

Figure 3: Structure of AgriVoltaics System with PLC and Sensors

These challenges highlight the need for a scalable and cost-effective smart agrivoltaics framework that seamlessly integrates PLCs, IoT sensing, and LoRaWAN communication. Such a system should leverage artificial intelligence to enhance water utilization, improve adaptive crop modeling, and optimize energy consumption. Addressing these gaps enables intelligent resource management, supports automation, and improves sustainability in next-generation agrivoltaic farming systems.

3.2. Proposed Method

Farming under sunlight panels usually means growing plants while catching solar energy at once. Though such setups manage both food output and clean electricity fairly well, they tend to miss smart watering controls, self-adjusting plant care, or built-in automation features. What changes things here is combining old-style sun-panel farms with networked sensors, live data links, and industrial control units that respond instantly.

with these pieces linked together, the whole system runs itself more smoothly - water gets used wisely, crops adapt faster, operations stay steady - all without stepping outside one connected farm space.

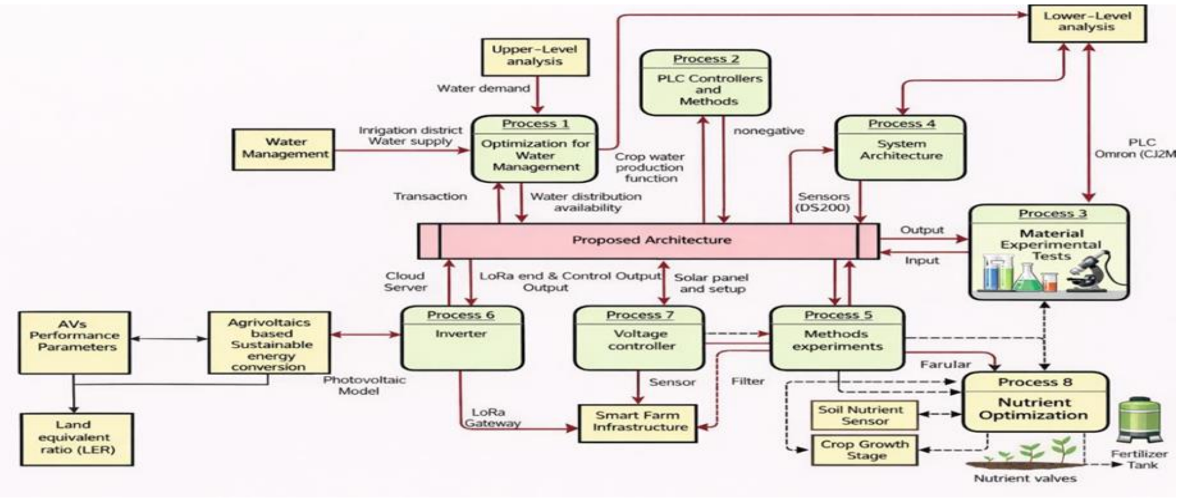

Figure 4: Overall Architecture of the Proposed Model

An overview of agricultural water needs is the first step in the proposed system's operating flow. This evaluation estimates the overall irrigation needs by taking crop demands and environmental factors into account. The best time and quantity of water supply are decided by **Process 1:** Optimization for Water Management based on this evaluation, guaranteeing effective use of the water resources that are available.

The optimized irrigation decisions are implemented through **Process 2:** PLC controllers implement the optimal irrigation choices by automating irrigation system control. PLCs take the best inputs and provide real-time control signals to irrigation valves and mechanisms, making water application precise and reliable. To ensure system robustness, **Process 3:** Material Experimental Tests tests system components such as pipes, sensors, and valves for strength and dependability in agricultural working conditions.

Soil moisture sensors, environmental sensors, and control valves are all integrated into **Process 4:** System Architecture, which defines the system's physical and control structure. The accurate control of water flow and ongoing field condition monitoring are made possible by these elements. Water delivery efficiency is further increased by examining irrigation improvement solutions including water enhancers and filtration techniques in **Process 5:** Methods and Experimental Techniques.

The integration of renewable energy is handled in **Process 6:** Photovoltaic Inverter, which transforms solar energy from photovoltaic panels into electrical power that may be used to run PLCs, sensors, and communication modules. **Process 7:** Voltage Controller and Monitoring continually monitors soil moisture levels and solar energy availability, enabling the system to modify irrigation schedules in response to crop water needs and energy supply.

To improve crop growth and soil health, **Process 8:** Nutrient Optimization concentrates on intelligent fertilizer management in addition to water management. To evaluate nutrient availability and plant requirements, this method makes use of real-time inputs from soil nutrient sensors and crop growth stage indicators. With the use of this data, automatic nutrient valves attached to a fertilizer tank calculate and supply the ideal amounts of nutrients. In order to achieve accurate fertigation, minimize nutrient losses, and increase nutrient usage efficiency, fertilizer delivery is coordinated with watering schedules.

By connecting all sensors, controllers, and actuators, a smart farming infrastructure allows for real-time monitoring and control. By sending sensor and control data to cloud servers for centralized processing and analysis, LoRa technology enables long-range, low-power communication. Across vast agricultural fields, this communication framework guarantees scalability and real-time decision-making.

By balancing the supply of fertilizer and irrigation with crop demand, the integrated water and nutrient management modules seek to reduce resource waste and preserve ideal growing conditions. Key performance metrics, such as the Land Equivalent Ratio (LER), which gauges land-use efficiency and combined agricultural–energy production, and agrivoltaics performance parameters, are used to assess the efficacy of the agrivoltaics system.

In order to guarantee operational effectiveness, dependability, and adaptive control, a lower-level analytical lastly continually verifies system performance using real-time sensor data. The entire architecture of intelligent agrivoltaic farming systems, backed by cloud servers and PLC-based automation, allows for better crop yield performance, sustainable resource use, and effective farm management.

3.2.1 Control System of a proposed method:

A 600 m² walnut growing plot was used for the investigation. Using a 5000 L booster pump, irrigation water was drawn from a well and transferred to a storage tank. To guarantee a clean water supply, water was transferred from the tank to the irrigation laterals via a filter unit. A control valve was fitted at the intake of each lateral pipe, enabling independent water flow adjustment. Solar photovoltaic panels with a 2.2 kW rating powered the whole irrigation system, adequately meeting the system's energy needs.

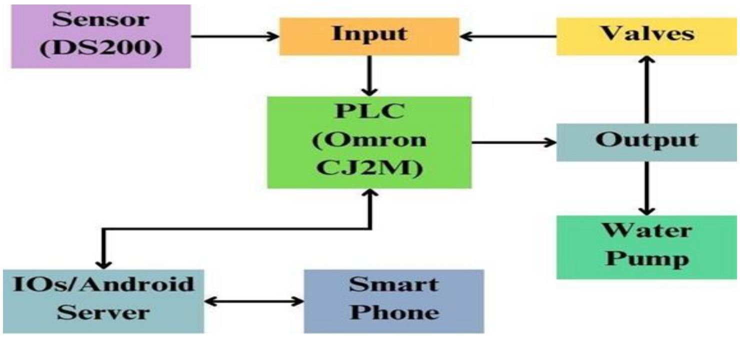

Figure 5: Control System Model

An advanced type of automated agriculture is a smart farm built on the Internet of Things (IoT). End-node sensors placed in the field, an IoT LoRa WAN gateway, a variety of control and actuation devices, and a cloud-based server that houses a web-enabled platform for system monitoring and data analysis make up the four primary components of the suggested system.

Additionally, a Telegram chat bot is incorporated to manage access via mobile devices and deliver real-time notifications. The suggested smart farming architecture is explained in depth after a brief introduction to LoRa and LoRa WAN technologies.

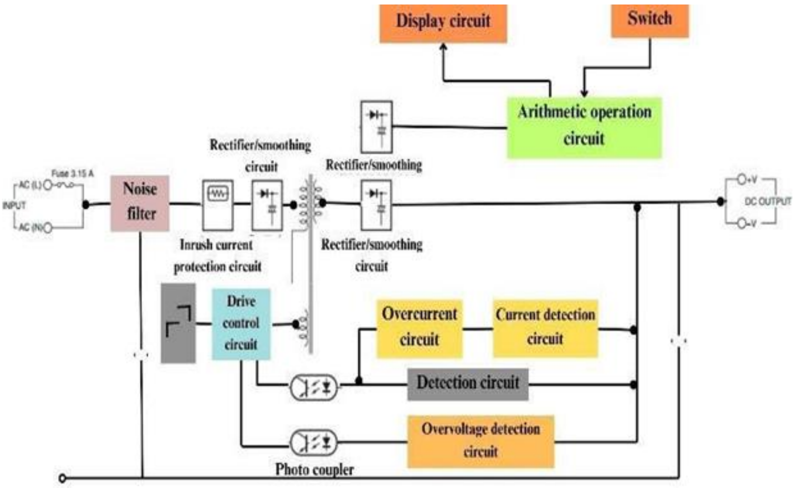

Figure 6: plc control unit

Farmers may monitor real-time data, examine past patterns, and manually override system processes if necessary thanks to online and mobile interfaces that facilitate user participation. Furthermore, to provide prompt user awareness, a Telegram bot interface offers real-time alerts and messages on irrigation events, system status, or issues.

All things considered, the figure shows a closed-loop smart farming system that incorporates cloud-based monitoring, clever control logic, low-power wireless connection, and strong hardware protection. By facilitating data-driven decision making, this integrated method lowers manual labor, increases water and energy efficiency, and promotes sustainable agriculture practices.

3.2.2 Smart Farm Infrastructure:

The two linked networks that make up the suggested smart farm architecture allow for both centralized control and real-time field monitoring. Important soil and ambient characteristics including moisture, temperature, humidity, ventilation, and pH are continually measured via a wireless sensor network based on LoRa. A LoRa gateway is used to send sensor data from the field and warehouse to the cloud for processing and archiving. Control commands are transmitted back to the PLC system via the gateway based on the processed data. The PLC ensures effective and responsive farm management by automatically operating machinery like air conditioners and irrigation pumps.

Figure 7: Smart Farm Infrastructure

While uniformly spaced LoRa sensor nodes offer precise and reliable data gathering, the LoRa gateway is positioned strategically at an elevated site to guarantee steady long-range connectivity. By gathering, processing, and sending sensor data for centralized monitoring and management, an IoT gateway connects field devices to the cloud. The LoRaWAN protocol guarantees low-power, secure, and encrypted communication that is appropriate for agricultural settings. Modbus TCP allows the Siemens Simatic IOT2040 and Siemens S7 PLC to reliably exchange data. The IOT2040 may function as a LoRa end-node by integrating an IMST WiMOD LoRa Arduino shield, guaranteeing smooth compatibility within the LoRa sensor network.

3.2.3 Experimental SetUp and Summary:

In order to assess a LoRa-based communication system's performance in actual agricultural conditions, the experimental research was conducted in a rural location close to Valencia, Spain. The LoRa gateway was placed at a height of around 24 meters to provide wide-area coverage, and an IMST LoRa Mote II device with GPS, temperature, accelerometer, and altimeter sensors served as the end-node.

The system used LoRaWAN Class A with a spreading factor of 7 and a bandwidth of 125 kHz to operate in the 867.1– 868.5 MHz frequency. The Received Packets Percentage (RPP) was used to assess packet delivery performance after measurements were taken at many sites with different distances from the gateway.

The results showed that a set spreading factor reduces communication reliability over long distances, highlighting the need of Adaptive Data Rate (ADR) for improving network capacity, energy economy, and transmission performance.

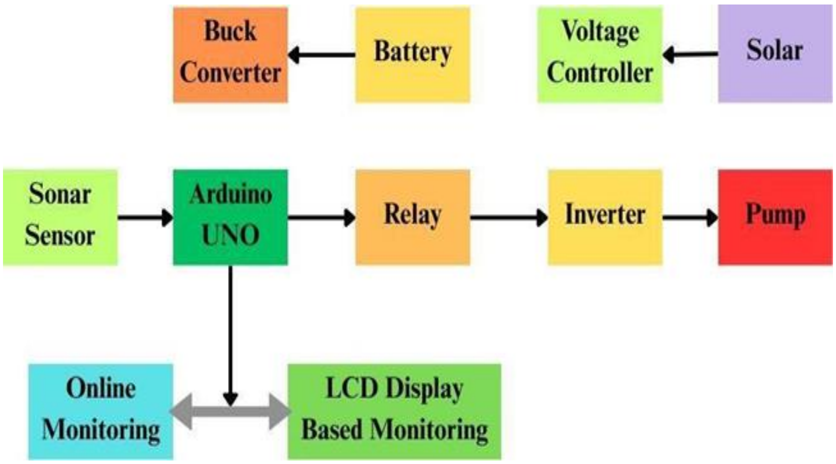

Figure 8: Experimental Test Setup

Signal attenuation and shadow fading effects were described using a large-scale fading model with first-order fitting, and route loss was also investigated using RSSI and SNR values. Wireless data transfer, relay-based pump control, LCD-based monitoring, and the use of renewable energy ensured dependable, sustainable, and efficient irrigation operation.

A solar-based energy management unit that includes photovoltaic panels, a voltage controller, battery storage, a buck converter, and fast-charging circuitry powers the irrigation subsystem. This arrangement lessens reliance on grid electricity while guaranteeing continuous functioning day and night. Depending on the observed water level and field conditions, an Arduino-based control unit interprets sensor data and triggers relays to automatically operate the inverter and pump motor. The system offers two visualization techniques for user engagement and monitoring. Real-time motor status and water level readings are shown on a local LCD display, and remote monitoring is made possible using mobile interfaces and a web-based platform. A Telegram bot is also used to give real-time messages and warnings, increasing user knowledge of irrigation events, system condition, and issues.

All things considered, the suggested solution creates a closed-loop, intelligent smart farming architecture that blends cloud-based intelligence, automated control, renewable energy use, and low-power long-range communication. This integrated method is ideal for large-scale and remote farming applications because it enhances the efficiency of water management, lowers energy consumption, decreases manual labor, and promotes sustainable agricultural practices.

4. Results

A. Energy Production Analysis :

The simulation's findings show that energy production is significantly higher in the early morning and late afternoon, and that power output decreases about lunchtime. Energy storage devices are used less frequently since this generating pattern coincides well with times when power demand is at its highest.

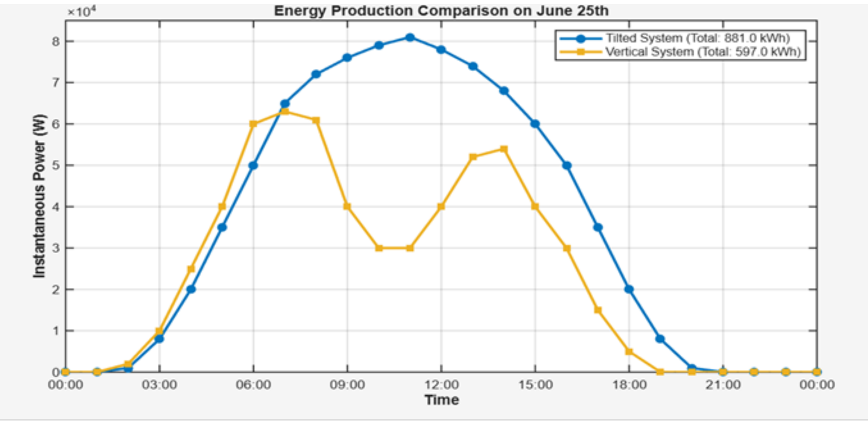

Figure 9: Energy Production Graph For Titled and Vertical System

When demand is strong, a larger percentage of the generated energy may be sent straight to the grid, increasing system efficiency and grid support capacity.

B . Average Spacing Analysis:

Crop growth, microclimate regulation, resource use, and total yield performance are all strongly impacted by row spacing, making it a crucial design element in agrivoltaic farming systems.

Crop rows spaced appropriately control air circulation, soil moisture distribution, and solar radiation penetration—all critical for preserving plant health and maximizing photosynthetic efficiency in photovoltaic systems. Using a bisection optimization approach backed by LoRaWAN-based sensor data, a comparison of 0.15 m and 0.18 m spacing was carried out in order to determine the most appropriate row spacing. One iterative numerical optimization methodology that effectively finds an ideal solution within a specified timeframe is the bisection method.

The following is a summary of the optimization process: **Step 1: Forming an objective**

Maximizing agricultural production (Y) while preserving optimal resource usage (R) is the key goal. The expression for this connection is:

$f(d) = Y(d) - R(d)$

where the row spacing is denoted by (d). The value of (d), which maximizes (f(d)), is the ideal spacing. **Step 2: Search interval initialization**

Based on past field observations and agronomic viability, the first search interval is set between 0.15 and 0.18 meters. **Step 3: Assessment at the halfway mark**

The interval's midpoint is determined as follows: $d = 0.165$ m .

Real-time sensor data, including as yield indicators, light intensity, and soil moisture, gathered over the LoRaWAN network, is used to assess crop performance at this spacing.

Step 4: Refinement through iteration

Iterative adjustments are made to the interval based on the observed sensor data until convergence is reached and the ideal spacing is determined.

The relative performance of various spacing combinations is depicted in these figure. The findings show that whereas decreased spacing values initially result in higher plant densities, they also increase competition for nutrients, water, and light. Greater spacing values consistently showed superior long-term performance across the examined designs.

In terms of sustainability, crop health, and effective resource use, 0.18 m spacing outperformed 0.15 m spacing, despite the latter producing better initial output. 0.18 m row spacing promotes better ventilation, balanced moisture availability, and consistent crop development, making it more appropriate for long-term agrivoltaic farming systems, according to ongoing monitoring utilizing the LoRaWAN sensor network.

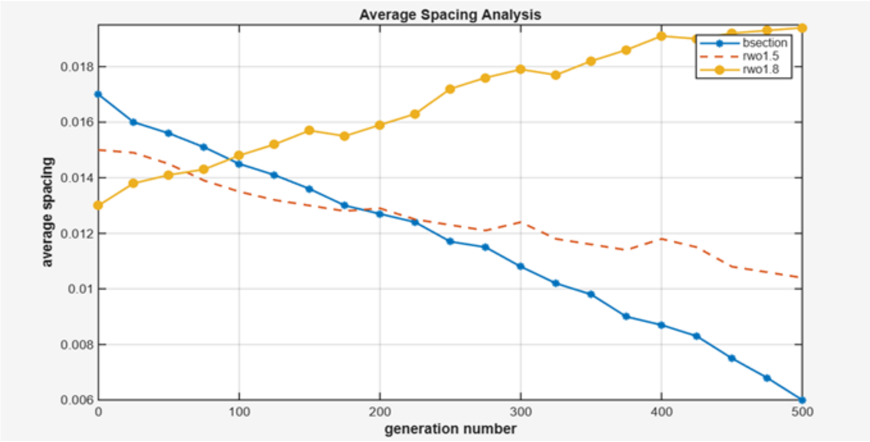

Figure 10: Average space Analysis for Planting

C. Irrigation Supply and Yield Production Analysis:

By comparing the suggested model's overall performance with that of the current approaches—IBPAS, RPARM, and SDSASM—it is assessed. The findings show that, out of all the strategies evaluated, the suggested method produces the best overall crop production. The model shows better water productivity in addition to increased output, suggesting more effective use of the water resources that are available

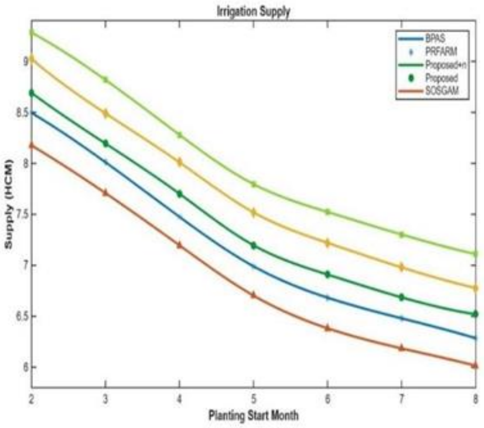

Figure 11(a): Irrigation Supply Analysis

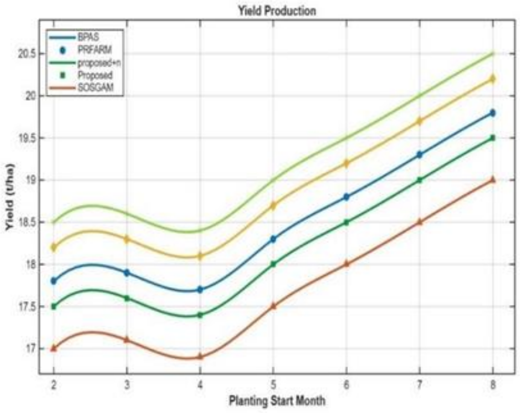

Figure 11(b): Yield Production Analysis

The planting area's improved yearly production performance is mostly due to the combined increase in yield and water-use efficiency.The suggested system performs better than traditional approaches in terms of sustainability and resource management by concurrently optimizing energy generation, irrigation control, and agricultural growing conditions.

These results demonstrate that the suggested model offers a well-rounded and effective way to maximize agricultural productivity while reducing water usage, which makes it ideal for long-term agrivoltaic farming applications.

D . Power Generation:

According to the findings, the suggested configuration produces noticeably more power than other methods already in use, including IBPAS, RPARM, and SDSASM.

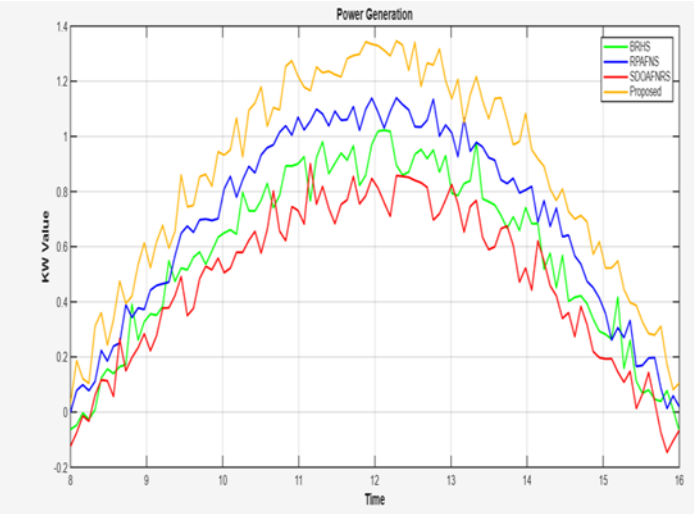

Figure 12: Power Generation

To ensure a thorough evaluation of sun exposure throughout the day, power generation performance was assessed for each of the installed photovoltaic panels on the eastern and western sides of the crop area. The study includes a beam shading factor, which takes into consideration partial shading effects brought on by panel orientation, crop height, and structural components, in contrast to traditional assumptions that prioritize early morning production.

A more accurate assessment of power production in real-world field settings is made possible by this method. The incorporation of foldable photovoltaic panels into the agrivoltaic system is the main factor responsible for the suggested model's higher energy efficiency. Because of its physical flexibility, panels may be oriented to maximize sun incidence and minimize crop shade. T

This setup facilitates efficient optimization of power generating data and enhances radiation collection. Furthermore, by synchronizing the functions of both fixed and foldable panels, the suggested approach effectively controls shadowing effects. This hybrid setup maintains ideal light levels for agricultural development while guaranteeing ongoing energy collecting. Approximately 16 hours are allotted for electricity generation each day, with the most productive time being 10 hours between 7:30 AM (sunrise) and 5:30 PM (sunset).

The suggested system's measured solar irradiance, which reflects actual outdoor working circumstances, varies from 0 to 1000 W/m². Figure 12 makes it clear that the suggested approach continuously produces more electricity than baseline systems at different irradiance levels. These findings attest to the increased power generation efficiency of the suggested agrivoltaic arrangement, which makes it a good fit for environmentally friendly energy production in agricultural settings.

E. Voltage and Current Analysis

Figure 11 displays the corresponding battery current profile. As is typical of a controlled charging process, the charging current showed a progressive decrease over time, in contrast to voltage. The current measured at the beginning of charging (0–5 minutes) was 0.49 A. After 10 minutes, this value dropped to 0.48 A, then to 0.43 A, and finally to 0.42 A after 20 minutes.

After half an hour, a second measurement revealed a further decrease to around 0.39A. The efficiency of the charge control and voltage regulation circuits, which ensure safe battery operation while avoiding overcharging, is validated by this pattern of decreasing current. The 10-minute trickle charging phase enables continuous operation by maintaining the battery at full capacity.

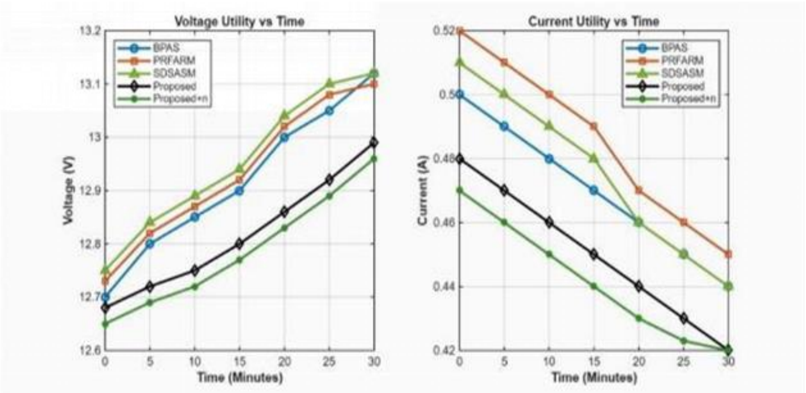

Figure 13: Voltage and Current Analysis

Overall, the observed voltage and current characteristics show that the suggested model outperforms current techniques in terms of electrical stability and charging reliability, offering stable and effective energy storage performance.

5. Conclusion and Discussion

An innovative method of managing renewable energy sources and sustainable agriculture is offered by the combination of Internet of Things (IoT) technologies with Power Line Communication (PLC) and LoRaWAN in agrivoltaic systems. In order to improve intelligent water management, dynamic crop modeling, fertilizer optimization, and communication efficiency in agrivoltaic environments, this study suggests an Internet of Things-driven agrivoltaic framework. The suggested system makes the best use of water, energy, and nutrients by utilizing real-time sensor data, AI-based analytics, and hybrid communication technologies. This improves irrigation effectiveness and raises agricultural production.

Large-scale agricultural activities may be reliably monitored and automated thanks to the suggested hybrid communication network, which combines LoRaWAN for long-range, low-power connectivity with PLC for high-speed data transfer. By continually assessing soil moisture, climate, and crop water requirements, the intelligent water management system optimizes irrigation schedule, minimizing water waste while preserving ideal crop health. Furthermore, by limiting nutrient losses, lowering environmental impact, and improving crop yield and water-use efficiency, the nutrient optimization module facilitates accurate, data-driven fertilizer application based on crop growth phases and soil nutrient status.

Additionally, farmers and policymakers may make better decisions because to the dynamic crop modeling framework's ability to adjust to shifting climatic and environmental conditions. MATLAB® simulations and real-world case studies are used for experimental evaluations, which show that the suggested approach greatly enhances precision farming results, water conservation, energy efficiency, and fertilizer usage. The results demonstrate how IoT-enabled agrivoltaic systems have a great deal of promise for tackling important issues with climate resilience, food security, and efficient land use.

The incorporation of blockchain technology for transparent and safe data sharing, edge computing for real-time processing and lower latency, and sophisticated artificial intelligence models for improved predictive analytics are some potential avenues for further study. The scalability and flexibility of the system will be further validated by extending it across other crop kinds and climate zones. Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), Long Short-Term Memory (LSTM) networks, and hybrid machine learning models are the most effective and resilient AI-based methods for predicting agrivoltaic crops.

References

[1] S.-H. Chae, H. J. Kim, H.-W. Moon, Y. H. Kim, and K.-M. Ku, “Agri voltaic systems enhance Farmers’ profits through broccoli visual quality and electricity production without dramatic changes in yield, antioxidant capacity, and glucosinolates,” Agronomy, vol. 12, no. 6, p. 1415,Jun.2022, doi: 10.3390/agronomy12061415.

[2] Y. Al Mashhadany, H. R. Alsanad, M. A. Al-Askari, S. Algburi, and B. A. Taha, “Irrigation intelligence-enabling a cloud-based Internet of Things approachfor enhancedwatermanagementinagriculture,” Environ. Monit. Assessment, vol. 196, p. 438, Apr. 2024, doi: 10.1007/s10661-024 12606-1.

[3] A. Scarano, T. Semeraro, A. Calisi, R. Aretano, C. Rotolo, M. S. Lenucci, A. Santino, G. Piro, and M. De Caroli, “Effects of the agrivoltaic system oncropproduction: Thecaseoftomato(SolanumlycopersicumL.),”Appl. Sci., vol. 14, no. 7, p. 3095, Apr. 2024, doi: 10.3390/app14073095

[4] B. A. Taha, N. M. Ahmed, R. K. Talreja, A. J. Haider, Y. Al Mashhadany, Q. Al-Jubouri, A. B. Huddin, M. H. H. Mokhtar, S. Rustagi A. Kaushik V. Chaudhary, and N. Arsad, “Synergizing nanomaterials and artificial intelligence in advanced optical biosensors for precision antimicrobial resistance diagnosis,” ACS Synth. Biol., vol. 13, no. 6, pp. 1600– 1620, Jun. 2024, doi: 10.1021/acssynbio.4c00070.

[5] M. Reasoner and A. Ghosh, “Agrivoltaic engineering and layout opti mization approaches in the transition to renewable energy technolo gies: A review,” Challenges, vol. 13, no. 2, p. 43, Sep. 2022, doi: 10.3390/challe13020043.

[6]K.Mehta, M. J. Shah, and W. Zörner, "Agri-PV (Agrivoltaics) in developingcountries:AdvancingsustainablefarmingtoaddresstheWater Energy–Food Nexus," Energies, vol. 17, no. 17, p. 4440, Sep. 2024, doi: 10.3390/en17174440.

[7] Y. A. Mashhadany, A. K. Abbas, and S. Algburi, "Study and analysis of power system stability based on FACT controller system," Indonesian J. Electr. Eng. Informat., vol. 10, no. 2, pp. 317–332, Jun. 2022, doi: 10.52549/ijeei.v10i2.3630.

[8] R.A.Gonocruz,R.Nakamura,K.Yoshino,M.Homma,T.Doi,Y.Yoshida, and A. Tani, "Analysis of the Rice yield under an agrivoltaic system: A case study in Japan," Environments, vol. 8, no. 7, p. 65, Jul. 2021, doi: 10.3390/environments8070065.

[9] Y.I. Al-Mashhadany and Y. Abdulhafedh Ahmed, "Optimal DC machines performance based on intelligent controller," IOP Conf. Ser., Mater. Sci. Eng., vol. 917, no. 1, Sep. 2020, Art. no. 012084, doi: 10.1088/1757 899x/917/1/012084.

[10] R. Mahto, D. Sharma, R. John, and C. Putcha, "Agrivoltaics: A climate smart agriculture approach for Indian farmers," Land, vol. 10, no. 11, p. 1277, Nov. 2021, doi: 10.3390/land10111277.

[11] R. K. Lama and H. Jeong, "Design and performance analysis of foldable solar panel for agrivoltaics system," Sensors, vol. 24, no. 4, p. 1167, Feb. 2024, doi: 10.3390/s24041167.

[12] Y. I. A. Mashhadany, "Optimal results presentation style for engineer ing research article," AIP Conf. Proc., vol. 2400, no. 1, Oct. 2022, Art. no. 040008, doi: 10.1063/5.0112145.

[13] M. A. Zainol Abidin, M. N. Mahyuddin, and M. A. A. Mohd Zainuri, "Solar photovoltaic architecture and agronomic managementinagrivoltaic system: A review," Sustainability, vol. 13, no. 14, p. 7846, Jul. 2021, doi: 0.3390/su13147846.

[14] C.DeFrancesco,L.Centorame,G.Toscano,andD.Duca,"Opportunities, technological challenges and monitoring approaches in agrivoltaics sys tems for sustainable management," Sustainability, vol. 17, p. 634, 2025, doi: 10.3390/su17020634.

[15] Y.I.AlMashhadany,F.Amir,andN.Anwer.(2014).Modeling,Simulation and Analysis of Excitation System for Synchronous Generator. [Online]. Available: www.ajouronline.com

[16] Y. Zhang, T. Chen, E. Gasparri, and E. Lucchi, "A modular agrivoltaics building envelope integrating thin-film photovoltaics and hydroponic urban farming systems: A circular design approach with the multi-objective optimization of energy, light, water and structure," Sustainability, vol. 17, no. 2, p. 666, Jan. 2025, doi: 10.3390/ su17020666. [17] B. B. Sharma, R. Raffik, A. Chaturvedi, S. Geeitha, P. S. Akram, L. Natrayan, V. Mohanavel, M. Sudhakar, and R. Sathyamurthy, "Design ing and implementing a smart transplanting framework using pro grammable logic controller and photoelectric sensor," Energy Rep., vol. 8, pp. 430–444, Nov. 2022, doi: 10.1016/j.egyr.2022.07.019.

[18] L. Xin, L. Guang, and Y. Ming, "Design on the precise regulating control system for moisture and nutrient of plants based on PLC," Phys. Pro., vol. 33, pp. 429–436, Jan. 2012, doi: 10.1016/j.phpro. 2012.05.085.