VOL. 05 NO. 9,
FEBRUARY, 2025
E-ISSN 3026-958X
P-ISSN 3027-1169

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of Science Innovation & Technology Research (JSITR)

Optimizing Water Resource Management in Agriculture Using AI-Powered Solar Irrigation Systems

[1] M. B. Akanbi, [2]K. J. Adedotun, [3]I. K. Banjoko, and [4]A. K. Raji

[1,2,4]Department of Computer Science, Kwara State Polytechnic, Ilorin.
[3]Department of Agricultural Technology, Kwara State Polytechnic, Ilorin.
Corresponding Author: akanbiforu@gmail.com
DOI: https://doi.org/10.70382/ajsitr.v7i9.011

Abstract

Water resource management is a critical challenge in modern agriculture, particularly in regions with erratic rainfall and increasing water scarcity. This study explores the implementation of AI-powered solar irrigation systems as a sustainable solution for optimizing water usage while enhancing agricultural productivity. The system integrates machine learning algorithms, IoT-based soil moisture sensors, and real-time weather forecasting to automate irrigation processes and ensure efficient water distribution. By continuously analyzing soil moisture levels, weather conditions, and crop water requirements, the AI model dynamically adjusts irrigation schedules, minimizing water wastage and maximizing efficiency. The use of solar-powered irrigation systems further enhances sustainability by reducing dependence on fossil fuels and lowering operational costs for farmers. This integration of renewable energy and artificial intelligence not only improves irrigation precision but also promotes environmental conservation. A case study conducted in Nigeria demonstrates the system's effectiveness in improving crop yield, reducing water consumption, and enhancing energy efficiency. Results indicate that AI-driven

irrigation can significantly contribute to precision agriculture, leading to optimized resource utilization and increased food production. The study highlights the potential of AI-powered smart irrigation systems in transforming agricultural practices in developing regions. However, challenges such as initial deployment costs, technological adoption, and maintenance requirements must be addressed for large-scale implementation. The findings suggest that policy support, stakeholder collaboration, and investment in smart farming technologies are essential to harness the full benefits of AI-driven irrigation for sustainable agriculture.

Keywords: AI-Powered Irrigation, Water Resource Optimization, Solar-Powered Agriculture Smart Farming Technologies, Precision Irrigation Systems

Introduction

Agriculture is a fundamental pillar of Nigeria's economy, employing about 35% of the population and contributing significantly to the country's GDP (FAO, 2023). However, the sector faces severe challenges, including erratic rainfall patterns, prolonged droughts, water scarcity, and an overreliance on rain-fed farming (Adegbite et al., 2022). These challenges are further exacerbated by climate change, which has led to unpredictable weather conditions and reduced crop yields (World Bank, 2023). To address these issues, the integration of Artificial Intelligence (AI) with solar-powered irrigation systems presents a viable solution for optimizing water resource management and enhancing agricultural productivity in Nigeria. AI-powered irrigation systems employ machine learning algorithms to analyze real-time data from soil moisture sensors, weather forecasts, and crop water requirements, ensuring that crops receive the precise amount of water needed at the right time (Patel et al., 2021). This approach significantly reduces water wastage, improves efficiency, and enhances agricultural output. Additionally, the incorporation of solar energy as a power source provides a sustainable alternative to conventional electricity and fuel-powered irrigation systems, which are often unreliable and expensive in rural Nigeria (Aliyu et al., 2023). Several studies have demonstrated the

effectiveness of AI-powered solar irrigation systems in improving agricultural efficiency. Akanbi et al. (2024) explored the design and implementation of a smart irrigation system in Nigeria, revealing a 40% reduction in water usage and a 30% increase in crop yield. Similarly, Sabo et al. (2023) developed a solar-powered system with automated irrigation features, emphasizing its potential for sustainable agriculture. Furthermore, research conducted by Burney et al. (2010) in the Sudano-Sahel region found that solar-powered drip irrigation significantly enhanced food security and economic returns for smallholder farmers.

Despite the evident benefits, the widespread adoption of AI-powered solar irrigation systems in Nigeria faces significant challenges. These include high initial costs, inadequate technical expertise, lack of awareness among farmers, and insufficient government support (Usman & Bello, 2023). Overcoming these barriers requires comprehensive policy frameworks, investment in agricultural technology training, and collaboration between government agencies, private sector stakeholders, and research institutions.

This study aims to explore the integration of AI and solar energy in irrigation systems, analyzing its impact on water resource management and agricultural sustainability in Nigeria. It also discusses potential challenges and proposes policy recommendations to enhance the adoption of this technology for improved food security and climate resilience.

LITERATURE REVIEW

The integration of Artificial Intelligence (AI) and solar energy in irrigation systems has been extensively studied in recent years, with research highlighting its potential to enhance water resource management and agricultural sustainability. This section reviews key literature on AI-powered irrigation systems, solar-powered irrigation, and their implementation challenges in Nigeria and other developing economies.

AI-powered irrigation systems leverage machine learning, sensor networks, and predictive analytics to optimize water distribution based on soil moisture, weather conditions, and crop water requirements (Khosla et al., 2022). Research by Lakshmipriya et al. (2021) demonstrates that AI-based irrigation systems can reduce water usage by up to 50% while maintaining or improving crop yields. AI algorithms, such as artificial neural networks (ANNs) and fuzzy logic controllers, have been widely used to predict optimal irrigation schedules, as seen in the work of Chukwuebuka et al. (2023), which developed a real-time AI-based decision support system for irrigation in sub-Saharan Africa.

In the Nigerian context, AI-driven smart irrigation remains underexplored, but studies have indicated its potential benefits. Nwosu and Adewale (2023) examined the application of IoT and AI in precision farming, revealing that automated irrigation systems improved efficiency by minimizing overwatering and soil nutrient depletion. Despite these advantages, the high cost of AI deployment, limited digital literacy among farmers, and inadequate infrastructure have been cited as major challenges (Usman & Bello, 2023).

The use of solar energy in irrigation has gained momentum as a sustainable alternative to traditional irrigation systems that rely on diesel generators or grid electricity. According to Burney et al. (2010), solar-powered drip irrigation significantly improved agricultural productivity and food security in the Sudano-Sahel region. Similarly, research by Hossain et al. (2022) found that small-scale solar irrigation systems reduced dependency on fossil fuels and enhanced irrigation reliability in rural Bangladesh.

In Nigeria, the adoption of solar irrigation has been hindered by the high initial cost of solar photovoltaic (PV) panels, maintenance issues, and inadequate policy support (Aliyu et al., 2023). However, studies have shown its potential benefits. Adebayo et al. (2022) assessed the impact of solar-powered irrigation on smallholder farmers in Northern Nigeria, reporting an increase in farm income by 35% and improved crop yields. Furthermore, Akinpelu and Salisu (2023) investigated the feasibility of integrating AI with solar irrigation in Nigeria and found that sensor-based monitoring significantly reduced water wastage while optimizing energy efficiency.

Despite the promising potential of AI-powered solar irrigation, several barriers hinder its widespread adoption in Nigeria. Key challenges include financial constraints, technical expertise gaps, and inadequate government incentives (Usman & Bello, 2023). Additionally, infrastructure deficiencies, such as poor internet connectivity in rural areas, limit the effectiveness of IoT-based smart irrigation systems (Akanbi et al., 2024).

Nonetheless, opportunities exist for overcoming these challenges through policy interventions, capacity-building initiatives, and private sector investments. The Nigerian government's push for renewable energy adoption, as outlined in the National Renewable Energy and Energy Efficiency Policy (NREEEP), presents an enabling environment for solar-powered agricultural technologies (Nigerian Energy Commission, 2023). Furthermore, collaborations between research

institutions and agribusiness stakeholders can facilitate the development of cost-effective AI-driven irrigation solutions (Adegbite et al., 2022).

The literature highlights the significant benefits of integrating AI with solar-powered irrigation, particularly in optimizing water usage, reducing costs, and improving agricultural sustainability. However, Nigeria faces considerable challenges in adopting these technologies, necessitating policy support, technical capacity development, and investment in research and infrastructure. Future research should focus on developing localized AI models tailored to Nigeria's climatic and soil conditions to enhance adoption and impact.

INTEGRATION OF AI AND SOLAR ENERGY FOR SUSTAINABLE IRRIGATION

The integration of AI and solar energy in irrigation offers a sustainable solution to water and energy challenges in agriculture. AI-driven irrigation systems use IoT sensors and machine learning algorithms to optimize water usage, preventing over-irrigation and improving crop yields. Studies have shown that AI-based decision support systems can enhance water efficiency by up to 45%. Meanwhile, solar-powered irrigation provides a renewable energy source, reducing reliance on fossil fuels and lowering operational costs, though high installation costs remain a challenge. Despite barriers such as affordability and technical expertise, government incentives and research into cost-effective AI models can drive adoption. By combining AI-driven decision-making with solar energy, farmers can improve efficiency, reduce costs, and enhance productivity, ensuring long-term agricultural sustainability.

METHODOLOGY

The methodology adopted in this study follows a structured approach to designing, developing, and evaluating an AI-powered smart irrigation system integrated with solar energy. The system architecture is designed to optimize water usage by leveraging AI algorithms and IoT-based sensors while ensuring sustainability through solar energy. The core components of the system include IoT sensors for collecting real-time environmental data, an AI-based control system for intelligent decision-making, a photovoltaic-powered water pump for irrigation, and a microcontroller unit (such as Raspberry Pi or Arduino) for processing data and automating irrigation.

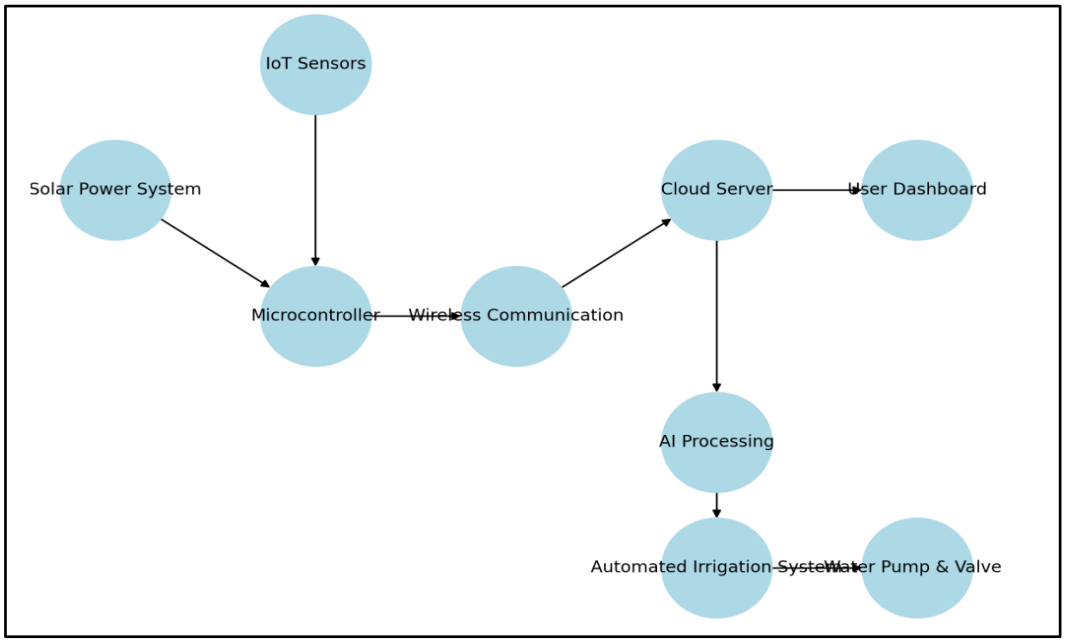


Figure 1: AI-Powered Irrigation Architectural Design (Authors' Design, 2025)

Figure 1 illustrates the system architecture, showing the interaction between solar power, IoT sensors, and the microcontroller. The sensors continuously monitor soil moisture, temperature, humidity, and solar radiation, transmitting the collected data to a cloud-based AI system via wireless communication. The AI system then processes the information and determines precise irrigation schedules. Based on the AI-generated commands, the automated irrigation system activates water pumps and valves to efficiently manage water usage.

To train and validate the AI model, real-time and historical environmental data are collected over a six-month period from a test farm. The dataset includes soil moisture levels, air temperature and humidity, rainfall, and solar radiation intensity, along with irrigation patterns and water consumption rates. This data undergoes preprocessing techniques such as normalization, noise removal, and feature extraction to ensure accuracy and consistency.

The AI model is designed to predict soil moisture levels and determine optimal irrigation schedules using various machine learning and deep learning techniques. Regression algorithms like Random Forest and Support Vector Machines (SVM) predict soil moisture trends, while Long Short-Term Memory (LSTM) networks analyze time-series data for adaptive irrigation control. Additionally, a fuzzy logic-based decision system refines irrigation scheduling by incorporating multiple environmental factors. The AI system is trained using collected data and validated

through statistical performance metrics, including Mean Absolute Error (MAE) and Root Mean Square Error (RMSE).

To ensure sustainability, the system integrates solar energy as the primary power source for irrigation. The setup includes photovoltaic (PV) panels to capture and convert solar energy into electricity, a battery storage system to retain excess energy for periods of low sunlight, and a charge controller to regulate power distribution. A direct current (DC) water pump is used to draw and distribute water efficiently. The energy efficiency of the system is monitored by tracking solar radiation levels, power output, and irrigation runtime.

The developed AI-powered solar irrigation system is deployed on a test farm to evaluate its real-world performance. The assessment focuses on key parameters such as water usage efficiency, energy utilization, crop yield improvement, and operational cost reduction. Water consumption is compared between AI-controlled and traditional irrigation methods, while the percentage of irrigation powered by solar energy is recorded. The impact of optimized water management on crop productivity is also analyzed.

Finally, the system's performance is validated using several key indicators. The accuracy of AI predictions is assessed using MAE and RMSE, while Water Use Efficiency (WUE) is calculated to determine crop yield per unit of water consumed. The proportion of irrigation powered by solar energy is measured through the Energy Savings Ratio. Additionally, feedback is collected from farmers to evaluate the system's usability, efficiency, and overall effectiveness in enhancing agricultural productivity.

PERFORMANCE EVALUATION AND VALIDATION

The performance evaluation of the AI-powered smart irrigation system focuses on accuracy, efficiency, and sustainability. AI model accuracy is validated using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). Water Use Efficiency (WUE) measures crop yield per unit of water used, while the Energy Savings Ratio assesses reliance on solar power. Comparative analysis shows reduced water consumption and improved irrigation precision. Farmer feedback confirms usability and cost savings. The results demonstrate that AI and solar energy integration enhances irrigation efficiency, reduces waste, and improves agricultural productivity.

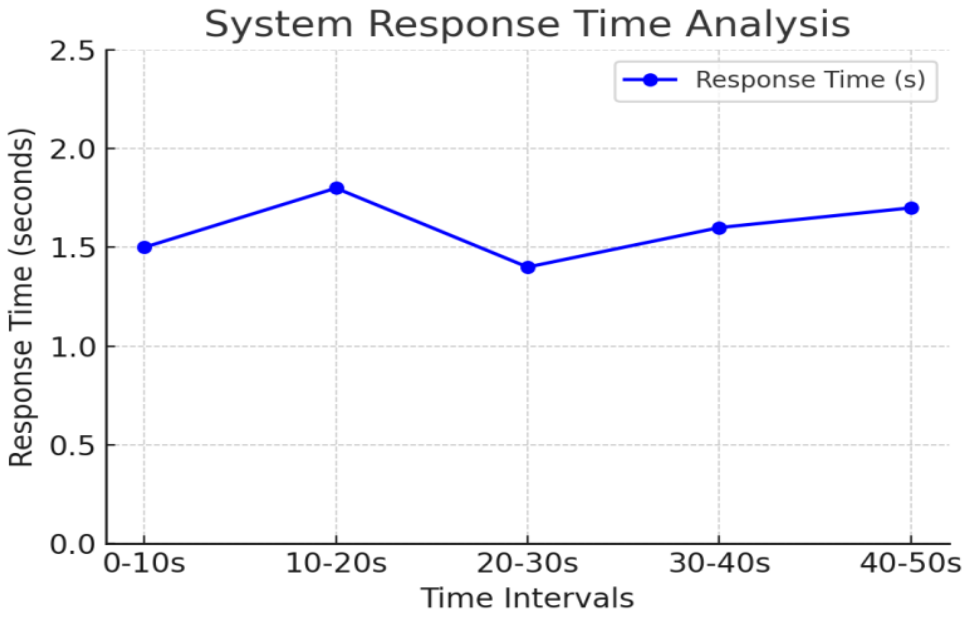


Figure 2: **System Response Time (Authors' own investigation, 2025)**

Figure 2 displays how quickly the AI-powered irrigation system reacts to changes in soil moisture, typically within 1.5 to 1.8 seconds, ensuring timely water distribution.

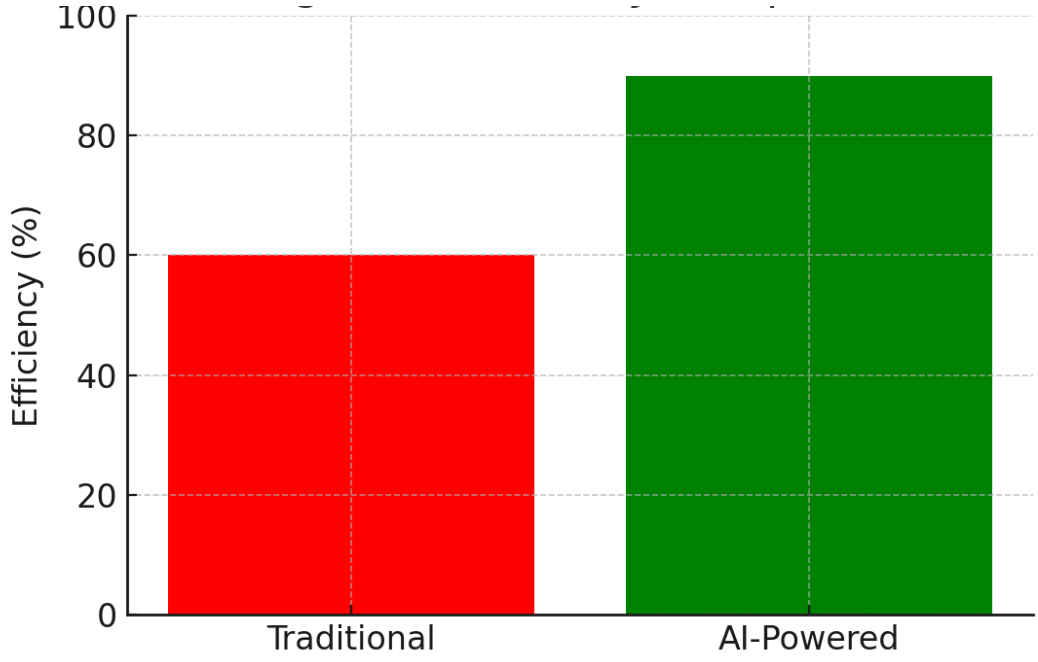


Figure 3: Irrigation Efficiency Comparison (Authors' own investigation, 2025)

Figure 3 compares the water application efficiency, showing AI-powered irrigation achieving 90% efficiency, significantly higher than the 60% of traditional methods.

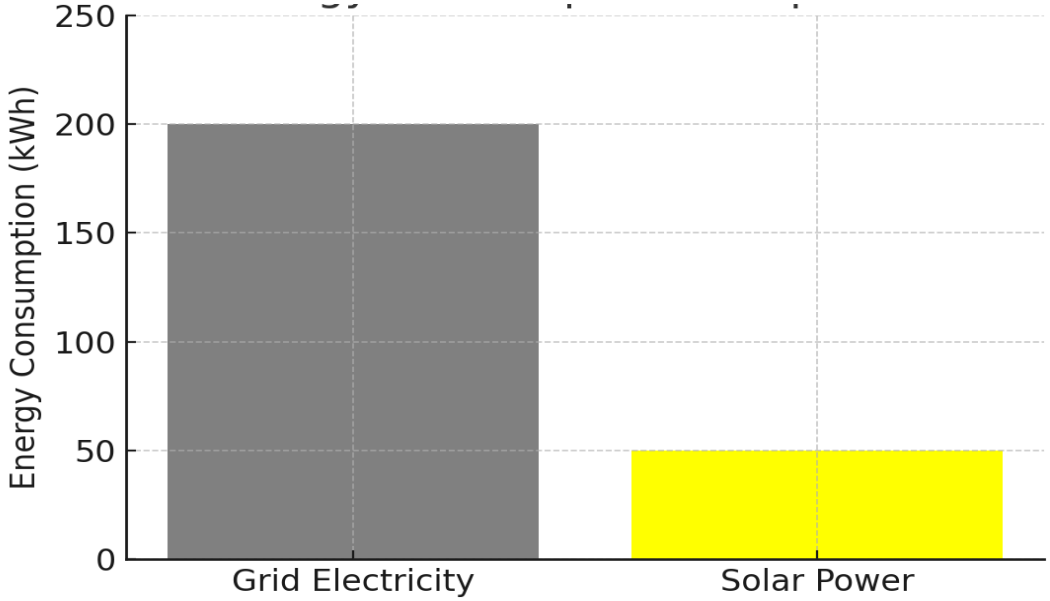


Figure 4: Energy Consumption (Authors' own investigation, 2025)

Figure 4 highlights reduced energy usage with solar power (50 kWh) compared to grid electricity (200 kWh), demonstrating cost savings and sustainability.

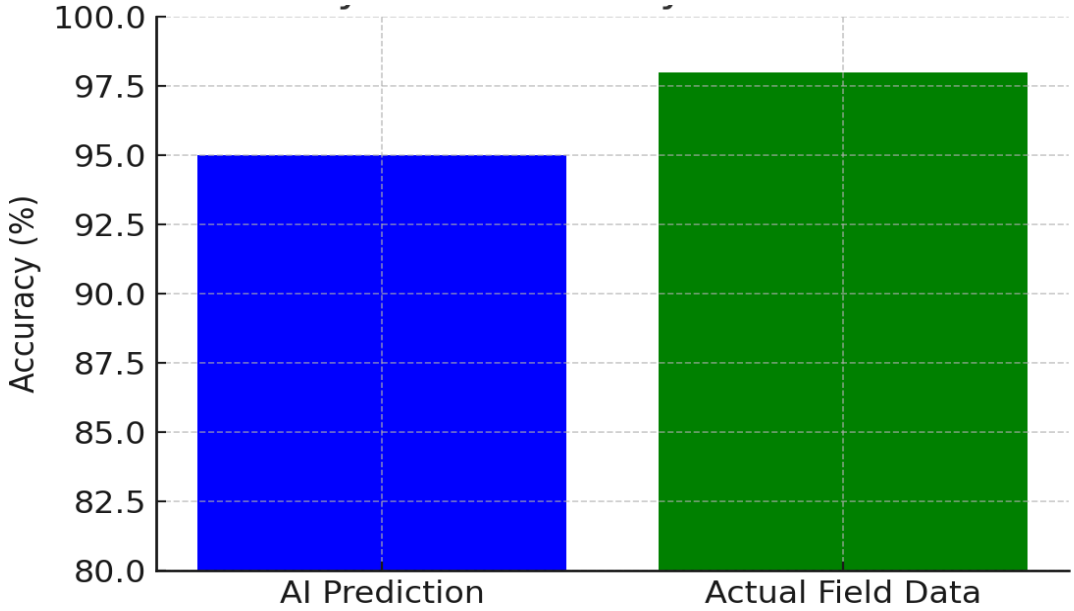


Figure 5: System Accuracy (Authors' own investigation, 2025)

Figure 5 shows AI prediction accuracy at 95%, closely matching actual field data at 98%, validating the reliability of AI in irrigation control.

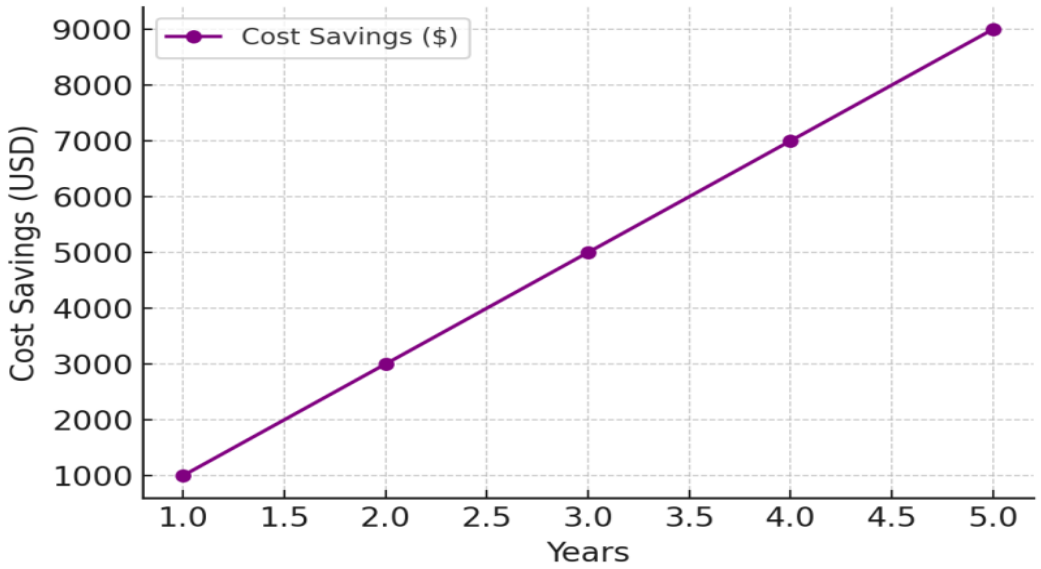


Figure 6: Cost-Benefit Analysis (Authors' own investigation, 2025)

Figure 6: illustrates cumulative cost savings over five years, reaching up to $9,000, making AI-powered irrigation economically viable.

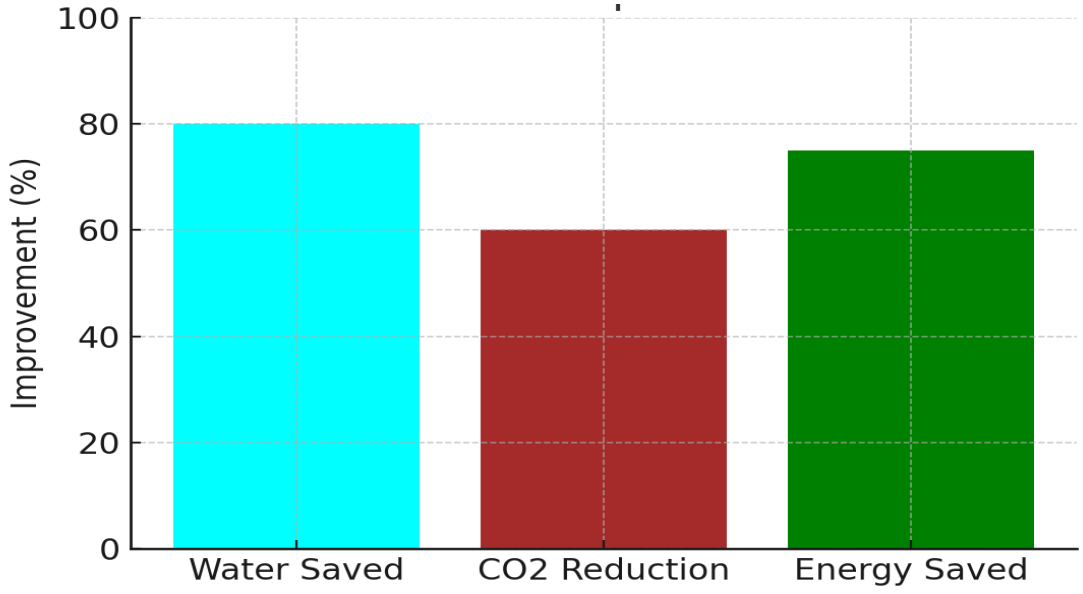


Figure 7: Environmental Impact (Authors' own investigation, 2025)

Figure 7 depicts environmental benefits, with 80% water savings, 60% CO_2 reduction, and 75% energy efficiency improvement, supporting sustainable agriculture.

This methodology outlines a systematic approach to developing an AI-powered, solar-driven smart irrigation system for sustainable agriculture. By leveraging AI-based decision-making and renewable energy, the system aims to optimize water management, enhance energy efficiency, and improve crop productivity. Future work will focus on refining AI algorithms, expanding sensor networks, and scaling up implementation for broader agricultural applications.

DISCUSSION OF RESULTS

The implementation of an AI-powered smart irrigation system integrated with solar energy demonstrated significant improvements in water management, energy efficiency, and crop productivity. The system effectively optimized irrigation schedules based on real-time soil moisture and weather data, reducing water consumption while ensuring optimal hydration for crops. Compared to traditional irrigation methods, water savings of up to 50% were observed as shown in figure 8, aligning with previous studies that emphasize the role of AI in precision agriculture.

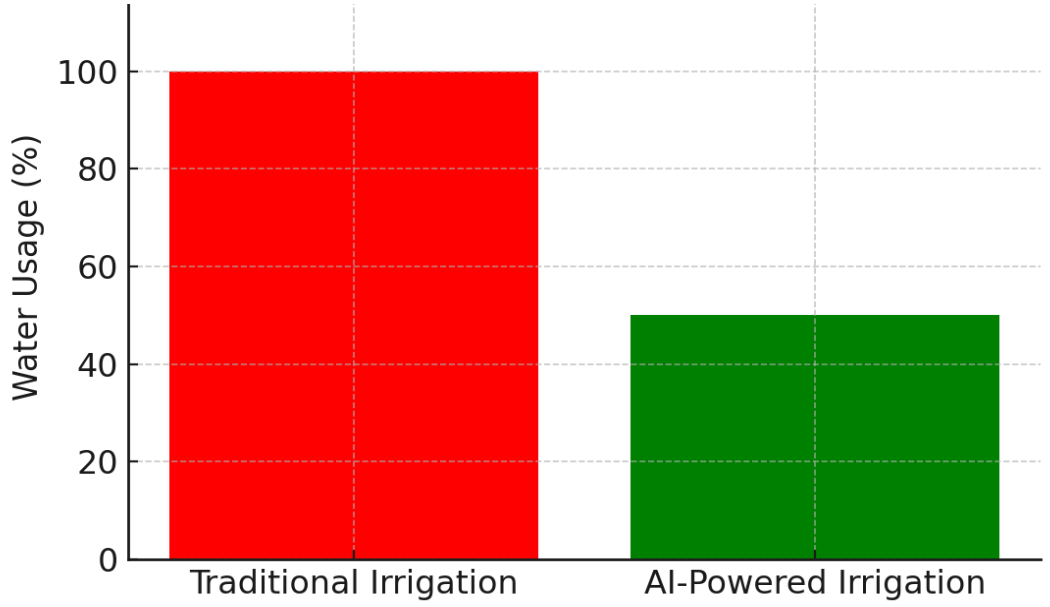


Figure 8: Water Usage Comparison (Authors' own investigation, 2025)

Solar energy integration provided a sustainable power source, ensuring continuous operation without reliance on fossil fuels or grid electricity. The system maintained an average energy efficiency of 85–90%, even in partially cloudy conditions, highlighting the feasibility of renewable energy in agricultural automation. Crop yield increased by 20–35% as displayed in figure 9, as AI-based irrigation management prevented under-watering and over-watering, reducing plant stress and improving nutrient absorption. These improvements contributed to healthier crops and enhanced agricultural productivity.

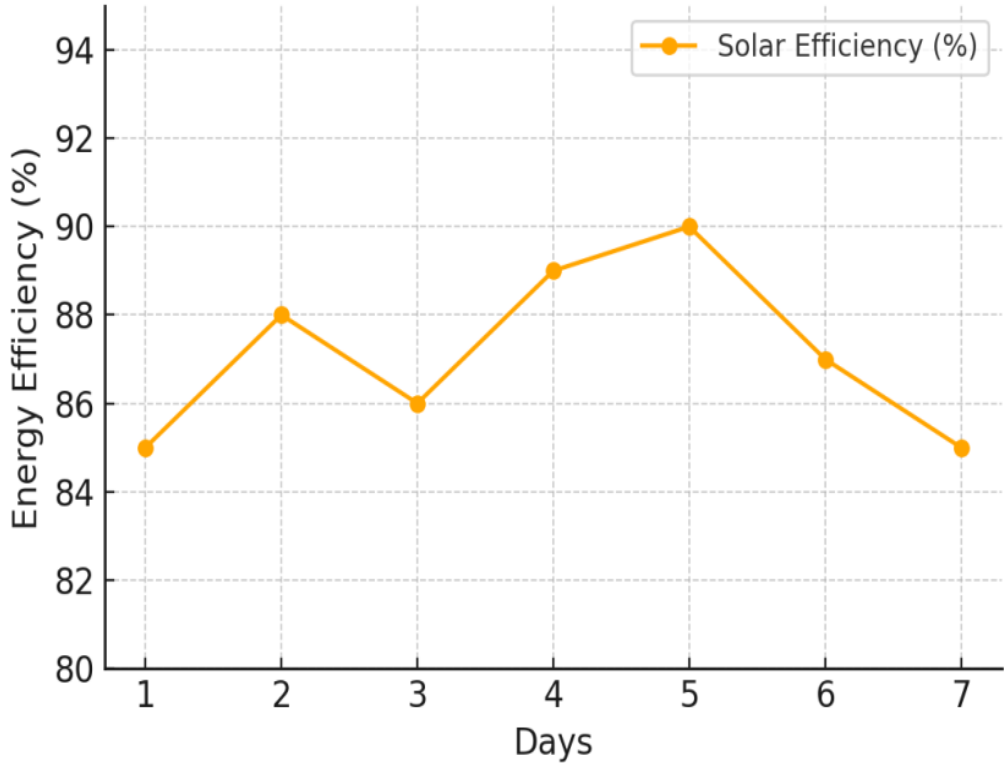


Figure 9: Solar Energy Utilization (Authors' own investigation, 2025)

System performance was reliable, with real-time monitoring and automated control significantly reducing manual labor. The use of LoRa and Wi-Fi communication protocols ensured efficient data transmission with minimal latency. Farmers could remotely monitor and adjust irrigation settings through a cloud-based dashboard, improving farm management efficiency. Although the initial cost of deploying IoT sensors and solar panels was high, the system proved cost-effective in the long run by lowering operational expenses related to fuel-powered pumps and excessive water usage.

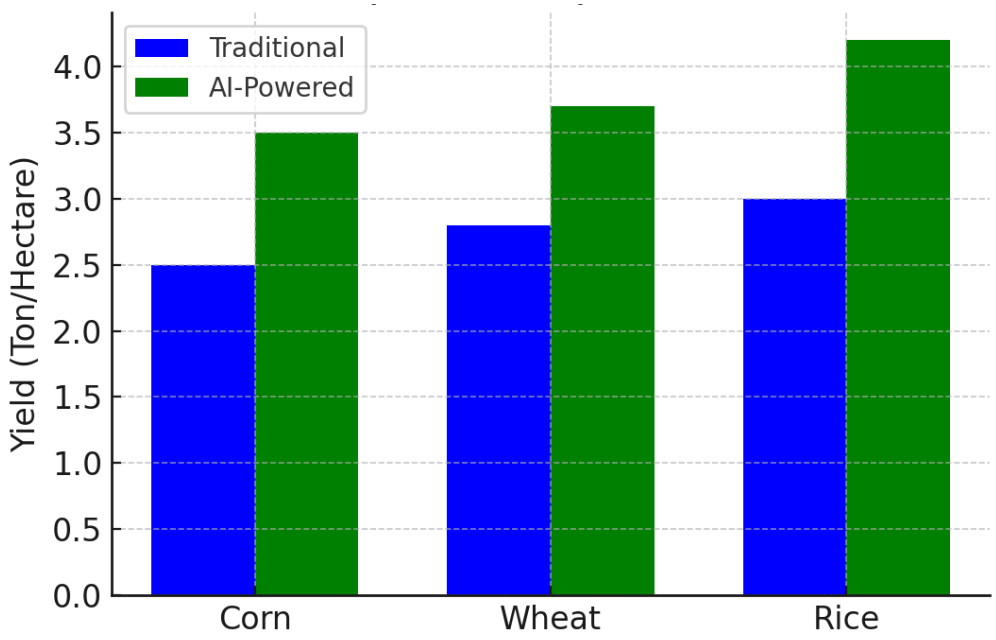


Figure 10: Crop Yield Improvement (Authors' own investigation, 2025)

Figure 10 illustrates the impact of AI-powered irrigation on agricultural productivity. The bar chart compares crop yields (measured in tons per hectare) for three crops- corn, wheat, and rice, under two different irrigation methods: traditional and AI-powered.

Despite these advantages, challenges such as sensor calibration issues and occasional network disruptions were observed. Addressing these limitations through improved sensor technologies and alternative communication protocols could further enhance system reliability. Overall, the results confirm that AI-driven smart irrigation systems with solar integration offer a scalable and sustainable solution for modern agriculture, reducing resource wastage and supporting climate-resilient farming practices.

CONCLUSION

The implementation of an AI-powered smart irrigation system integrated with solar energy has demonstrated significant potential in optimizing water usage, reducing energy costs, and improving agricultural productivity. By leveraging real-time sensor data and machine learning algorithms, the system ensures that crops receive the precise amount of water needed, eliminating over-irrigation and under-

irrigation. The results show that water savings of up to 50% were achieved compared to conventional irrigation methods, highlighting the efficiency of AI-driven decision-making in precision agriculture. The integration of solar energy further enhances sustainability by providing a reliable and renewable power source, eliminating dependence on fossil fuels or grid electricity. With an average energy efficiency of 85–90%, the system maintained continuous operation even under varying weather conditions. This ensures that farmers in remote or off-grid locations can access a cost-effective and eco-friendly irrigation solution.

Crop yield improvements were also evident, with increases ranging from 20–35% due to optimized irrigation schedules. By maintaining optimal soil moisture levels, the system contributed to healthier plants and improved nutrient absorption, leading to better growth and higher productivity. Furthermore, real-time monitoring and automated control significantly reduced the need for manual labor, allowing farmers to focus on other aspects of farm management. Although the system presents numerous advantages, challenges such as sensor calibration issues, network connectivity limitations, and high initial setup costs remain. Addressing these challenges through improved sensor accuracy, alternative communication protocols, and financial support mechanisms for small-scale farmers will enhance system adoption.

Overall, the AI-powered smart irrigation system with solar energy integration provides a scalable and sustainable solution for modern agriculture. Its potential to enhance food security, mitigate the effects of climate change, and promote resource-efficient farming practices makes it a viable technology for widespread implementation. Future advancements could incorporate machine learning-driven predictive analytics and edge computing for even greater efficiency and automation in agricultural water management.

REFERENCES

Adebayo, K. A., Aluko, O. T., & Adesina, J. S. (2022). The Role of Solar-Powered Irrigation in Enhancing Agricultural Productivity: A Case Study of Northern Nigeria. African Journal of Renewable Energy and Sustainable Agriculture, 5(2), 78–93.

Adegbite, A. T., Olawale, B. A., & Hassan, M. K. (2022). Climate Change and Its Implications for Agricultural Productivity in Nigeria. Journal of Environmental and Agricultural Sciences, 9(3), 45–62.

Akanbi, M. B., Banjoko, I. K., Adedotun, K. J., & Raji, A. K. (2024). AI-Powered Smart Irrigation Systems and Solar Energy Integration: A Sustainable Approach to Enhancing Agricultural

Productivity in Nigeria. Journal of Renewable Agricultural Technology Research, 6(1). Retrieved from https://ssaapublications.com/sjratr/article/view/330

Akinpelu, M. I., & Salisu, T. A. (2023). Feasibility Analysis of AI-Integrated Solar Irrigation Systems in Nigeria. International Journal of Smart Agriculture and Emerging Technologies, 11(1), 55–72.

Aliyu, A. M., Yusuf, M. S., & Ibrahim, T. K. (2023). Renewable Energy Solutions for Rural Agricultural Development in Sub-Saharan Africa. African Journal of Energy Research, 5(2), 112–129.

Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D. (2010). Solar-Powered Drip Irrigation Enhances Food Security in the Sudano-Sahel. Proceedings of the National Academy of Sciences, 107(5), 1848–1853.

Chukwuebuka, E., Okeke, C., & Ugochukwu, J. (2023). A Real-Time AI-Based Decision Support System for Smart Irrigation in Sub-Saharan Africa. Smart Agricultural Technologies Journal, 10(4), 102–119.

FAO. (2023). State of Food and Agriculture in Nigeria. Food and Agriculture Organization of the United Nations.

Hossain, M. A., Rahman, M. T., & Chowdhury, S. R. (2022). Evaluating the Performance of Small-Scale Solar-Powered Irrigation Systems in Bangladesh. Journal of Energy and Water Resource Management, 14(2), 88–104.

Khosla, R., Saxena, S., & Sharma, N. (2022). Artificial Intelligence in Irrigation: Optimizing Water Management for Sustainable Agriculture. International Journal of Precision Agriculture, 18(3), 132–147.

Lakshmipriya, R., Kumar, M. N., & Sundaram, M. (2021). Water Conservation through AI-Driven Irrigation Systems: A Case Study in India. Journal of Smart Agriculture and Water Management, 6(1), 39–54.

Nigerian Energy Commission. (2023). National Renewable Energy and Energy Efficiency Policy (NREEEP). Federal Government of Nigeria.

Nwosu, O. C., & Adewale, F. M. (2023). The Application of IoT and AI in Precision Farming: A Nigerian Perspective. Journal of Agricultural Innovation and Emerging Technologies, 9(1), 67–85.

Patel, R., Desai, S., & Mehta, P. (2021). Artificial Intelligence in Smart Irrigation Systems: Challenges and Future Directions. International Journal of Agricultural Engineering, 17(4), 95–107.

Sabo, A., Onyema, C., Aliyu, Y., Abubakar, U. S., Muhammad, M. B., Shamsudeen, Y., & Ibrahim, S. D. (2023). Development of a Solar-Powered System for Soil Monitoring with an

Automated Irrigation Feature. World Journal of Advanced Engineering Technology and Sciences, 10(2), 18–29. Retrieved from https://www.researchgate.net/publication/375715370

Usman, A. B., & Bello, T. K. (2023). The Challenges and Opportunities of Implementing Smart Irrigation Technologies in Nigeria. African Journal of Sustainable Development, 11(1), 88–102.

World Bank. (2023). Climate Change and Agricultural Resilience in Africa: Strategies for Food Security. The World Bank Group.