Review Article

Harnessing AI-powered smart irrigation systems to boost agricultural production and combat climate change in Nigeria: a comprehensive literature review

Abstract

Nigeria's agricultural sector is increasingly vulnerable to climate change, manifesting in erratic rainfall, prolonged droughts, and water scarcity. These challenges, compounded by the nation's dependence on rain-fed farming, threaten food security and rural livelihoods. Innovative, climate-resilient solutions are essential to transform agricultural productivity and sustainability. This literature review investigates the integration of Artificial Intelligence (AI) with solar-powered irrigation systems as a strategic approach to enhance water resource management, improve crop yields, and mitigate climate change impacts in Nigeria. The study synthesizes existing research and case studies on AI-driven irrigation systems powered by solar energy. It examines the technical components—including IoT sensors (soil moisture, temperature, rainfall), data acquisition modules, cloud-based AI platforms for predictive analytics, and automated irrigation infrastructure. The review also explores enabling technologies such as remote sensing, drones, cloud computing, and big data analytics, emphasizing their role in system intelligence and operational efficiency. Evidence from case studies, notably those by Akanbi et al.,[1] demonstrates substantial benefits: water usage reductions of up to 40%, crop yield increases of up to 30%, and water conservation improvements reaching 70%. The integration of solar energy significantly lowers greenhouse gas emissions and enhances system viability in off-grid rural areas. These systems also improve resilience by enabling dynamic responses to weather variability and promoting sustainable land management. To facilitate widespread adoption, the study recommends targeted interventions including government incentives, public-private partnerships, localized AI model development, rural infrastructure expansion, farmer training programs, and innovative financing mechanisms. Addressing barriers such as high initial costs, limited connectivity, and low technical literacy is critical to unlocking the full potential of AI-integrated solar irrigation systems in Nigeria.

Keywords: AI-powered smart irrigation, agricultural production, climate change, sensors

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Introduction

Agriculture stands as a cornerstone of Nigeria's economy, providing livelihoods for a significant portion of its population and contributing substantially to the nation's Gross Domestic Product (GDP).[2] Despite its pivotal role, the agricultural sector in Nigeria is grappling with a myriad of formidable challenges. These include erratic rainfall patterns, prolonged periods of drought, pervasive water scarcity, and an overarching overreliance on rain-fed farming practices.[3] These pre-existing vulnerabilities are further exacerbated by the profound and escalating impacts of climate change, which manifest as increasingly unpredictable weather conditions and a discernible reduction in overall crop yields.[4] The confluence of these factors poses a severe threat to Nigeria's food security, economic stability, and the well-being of its agrarian communities.

In the face of these pressing challenges, the integration of cutting-edge Artificial Intelligence (AI) technologies with solar-powered irrigation systems emerges as a highly promising and viable solution. This innovative synergy offers a sustainable pathway for optimizing water resource management, significantly enhancing agricultural productivity, and building resilience against the adverse effects of climate change. AI-powered smart irrigation systems leverage sophisticated machine learning algorithms, real time data from Internet of Things (IoT) sensors, and advanced weather forecasting models to automate and precisely control irrigation processes. This intelligent approach ensures that crops receive the exact amount of water they need, precisely when and where it is needed, thereby minimizing water wastage and maximizing efficiency.[5] Furthermore, the incorporation of solar energy as a primary power source for these irrigation systems provides a sustainable and environmentally friendly alternative to conventional electricity grids or expensive and often unreliable fuel-powered pumps, which are particularly prevalent in rural Nigerian contexts.[6]

The potential benefits of such integrated systems are manifold and far-reaching. Studies have already demonstrated the tangible positive impacts of AI-powered solar irrigation. For instance, research conducted by Akanbi et al.,[1] in Nigeria revealed a remarkable 40% reduction in water usage coupled with a 30% increase in crop yield. Similarly, Sabo et al.[7] developed a solar-powered system with automated irrigation features, underscoring its potential for fostering sustainable agriculture. Beyond Nigeria, the efficacy of solar-powered drip irrigation has been highlighted in regions like the Sudano-Sahel, where it significantly enhanced food security and economic returns for smallholder farmers.[8]

Despite these compelling advantages and the evident promise, the widespread adoption of AI-powered solar irrigation systems in Nigeria is not without its significant hurdles. Key challenges include the high initial costs associated with deployment, a notable lack of adequate technical expertise among farmers, insufficient awareness regarding the benefits of these technologies, and a perceived dearth of robust government support.[9] Overcoming these barriers necessitates a

concerted and multi-faceted approach, encompassing comprehensive policy frameworks, strategic investments in agricultural technology training and capacity building, and collaborative efforts among government agencies, private sector stakeholders, and research institutions.

This literature review aims to provides a comprehensive analysis of AI-powered smart irrigation systems, emphasizing their relevance and impact within Nigeria's agricultural sector. It explores the technical architecture of these systems, highlights their proven benefits in enhancing crop productivity and climate resilience, and critically assesses the challenges and opportunities for broader adoption across the country. Drawing on recent literature from the past five years, the review synthesizes key findings to identify best practices, policy interventions, and future research pathways. The focus includes AI applications in smart irrigation, solar-powered technologies, and their implications within Nigerian and Sub-Saharan agricultural contexts. Technical, environmental, and socio-economic impacts are evaluated to understand how these innovations can improve water efficiency, crop yields, and sustainability, while identifying gaps and strategies for future development.

Methodology

Research design

A qualitative, exploratory approach was adopted, using thematic synthesis to analyse literature from 2020–2025.

Data collection

I. Sources: Peer-reviewed journals, technical reports, pilot studies, and institutional publications.

II. Databases: Scopus, IEEE Xplore, Google Scholar

III. Inclusion Criteria: AI in irrigation, solar integration, Nigerian relevance, empirical metrics

IV. Exclusion Criteria: Non-agricultural AI, outdated or non-technical studies

Analytical framework

The literature was analysed across four dimensions:

I. Technical Architecture: IoT sensors, cloud platforms, AI models, solar integration

II. Impact Assessment: Crop yield, water savings, energy efficiency, climate metrics

III. Implementation Challenges: Financial, infrastructural, technical, policy-related

IV. Opportunity Mapping: Government incentives, PPPs, localized AI models

Validation and ethics

Findings were triangulated across sources and ethically synthesized with proper citation and transparency.

Literature review

Technical foundations of AI-powered smart irrigation systems

AI-powered smart irrigation systems represent a paradigm shift from traditional, often inefficient, irrigation methods to highly precise and adaptive water management strategies. These systems are built upon a foundation of interconnected technologies, primarily leveraging the Internet of Things (IoT), Artificial Intelligence (AI) algorithms, and advanced data analytics to optimize water delivery and enhance agricultural productivity.[10] The core objective is to provide crops with the exact amount of water they need, precisely when and where it is required, thereby minimizing waste and maximizing efficiency.

System architecture and components

The typical architecture of an AI-powered smart irrigation system involves several key components working in synergy:

I. **IoT Sensors**: These are the frontline data collectors, deployed across agricultural fields to gather real-time environmental and plant-specific data. Common sensors include: Soil Moisture Sensors: Measure the volumetric water content in the soil, providing crucial information about the immediate water needs of plants. Different types, such as capacitance or time-domain reflectometry (TDR) sensors, are employed for varying levels of accuracy and cost.[11]

II. **Temperature and humidity sensors**: Monitor ambient air temperature and humidity, which influence evapotranspiration rates and, consequently, crop water requirements.

III. **Rainfall sensors**: Detect precipitation events, allowing the system to automatically adjust or halt irrigation schedules to prevent overwatering.

IV. **Solar radiation sensors**: Measure incoming solar radiation, a key factor in determining potential evapotranspiration. Nutrient Sensors: (Advanced systems) Monitor soil nutrient levels, enabling integrated nutrient and water management.

V. **Data collection module**: This component aggregates data from various IoT sensors. It often involves microcontrollers like Raspberry Pi or Arduino, which process raw sensor data and prepare it for transmission. Wireless communication protocols such as Wi-Fi, LoRa (Long Range), or cellular networks are used to transmit this data to a central processing unit or cloud platform.[1]

VI. **Cloud-based AI system**: The collected data is transmitted to a cloud computing platform (e.g., AWS, Azure, Google Cloud) for storage, processing, and analysis. Cloud infrastructure provides the necessary scalability and computational power to handle large volumes of real-time and historical agricultural data.

AI model (Machine learning and deep learning): This is the brain of the smart irrigation system. Machine learning (ML) and deep learning (DL) algorithms are trained on vast datasets comprising historical weather patterns, soil characteristics, crop types, growth stages, and past irrigation performance. These models perform several critical functions:

I. **Predictive analytics**: Algorithms like Random Forest, Support Vector Machines (SVM), and Long Short-Term Memory (LSTM) networks are used to predict future soil moisture levels, crop water demand, and potential environmental stressors. For instance, SVMs can be trained on labeled datasets of healthy and diseased plants to detect early signs of crop diseases, which can influence irrigation decisions.[12]

II. **Decision-making**: Based on the predictions and real-time data, the AI model determines optimal irrigation schedules. Fuzzy logic controllers are often employed to integrate multiple,

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sometimes conflicting, environmental factors and make nuanced decisions about water allocation.[13] Optimization: The AI continuously refines its decisions to minimize water usage while maximizing crop health and yield. This involves dynamic adjustments to irrigation duration, frequency, and volume.

III. Automated irrigation system: This comprises the physical infrastructure responsible for water delivery. It includes:

IV. Water pumps: Often powered by photovoltaic (PV) panels in solar-integrated systems, these pumps draw water from sources like boreholes, rivers, or reservoirs.

V. Valves and actuators: Electronically controlled valves regulate the flow of water to specific zones or individual plants, enabling precise water distribution (e.g., drip irrigation or micro-sprinklers).

VI. Controllers: Microcontrollers receive commands from the AI system and activate the pumps and valves accordingly.

VII. Solar energy integration: For sustainable operation, especially in off-grid or rural areas like much of Nigeria, solar power is a crucial component. This integration typically includes:

VIII. Photovoltaic (PV) panels: Convert sunlight into electricity to power the entire system, including sensors, communication modules, AI processing units, and water pumps.

IX. Battery storage: Stores excess energy generated during daylight hours for use during night time or cloudy periods, ensuring continuous system operation.

X. Charge controller: Regulates the flow of electricity from the solar panels to the batteries and the system components, preventing overcharging or deep discharging of batteries.

Operational flow

The operational flow of an AI-powered smart irrigation system can be summarized as follows:

I. Data acquisition: IoT sensors continuously collect real-time data on soil moisture, temperature, humidity, rainfall, and solar radiation from the field.

II. Data transmission: The collected data is transmitted wirelessly to a central data collection module and then to a cloud based AI system.

III. Data analysis and prediction: The AI system processes the incoming data, integrates it with historical data and weather forecasts, and uses ML/DL models to predict crop water requirements and optimal irrigation timings.

IV. Decision-making: The AI model makes intelligent decisions regarding irrigation schedules, considering factors like current soil moisture deficit, crop growth stage, predicted evapotranspiration, and weather conditions.

V. Automated action: Based on the AI's decisions, commands are sent to the automated irrigation system, which activates water pumps and controls valves to deliver the precise amount of water to the designated areas.

VI. Feedback loop: The system continuously monitors the impact of irrigation, and the new sensor data feeds back into the AI model, creating a continuous learning and optimization loop. This adaptive nature allows the system to respond dynamically to changing environmental conditions and crop needs.

Key technologies and their roles

I. Internet of things (IoT): IoT forms the backbone of data collection, enabling real-time monitoring of various agricultural parameters. Sensors provide the raw data that AI algorithms process to make informed decisions. The connectivity provided by IoT allows for remote monitoring and control, which is particularly beneficial for large farms or in areas with limited human resources.[14]

II. Artificial intelligence (AI): AI, encompassing machine learning and deep learning, is central to the system's intelligence. It transforms raw data into actionable insights, enabling predictive analytics for yield forecasting, disease detection, and optimizing input application. AI algorithms can identify patterns in vast datasets that would be imperceptible to human observation, leading to highly efficient and precise irrigation (Kamilaris *et al*., 2018).

III. Remote sensing and drones: Satellite imagery and Unmanned Aerial Vehicles (UAVs), or drones, equipped with various sensors (e.g., multispectral, thermal) provide aerial perspectives of crop health, growth patterns, and stress factors. This macro-level data complements ground-based IoT sensor data, offering a comprehensive view of the farm. Drones can also be used for precise application of water or nutrients in specific areas identified by AI analysis.[15]

IV. Cloud computing: Provides the scalable computational resources and storage necessary for processing and analyzing the large volumes of data generated by IoT sensors and remote sensing. It also facilitates the deployment and management of AI models and enables remote access to farm data and control systems.

V. Big data analytics: The sheer volume, velocity, and variety of data generated by smart irrigation systems necessitate big data analytics techniques. These techniques allow for the extraction of meaningful patterns, correlations, and insights from complex datasets, further enhancing the accuracy and effectiveness of AI models.

In summary, the technical sophistication of AI-powered smart irrigation systems lies in their ability to integrate diverse technologies into a cohesive and intelligent framework. This integration enables unprecedented levels of precision, efficiency, and sustainability in agricultural water management, offering a powerful tool to address the challenges of food production and climate change.

Impact on agricultural production and climate change mitigation

The implementation of AI-powered smart irrigation systems has a transformative impact on agricultural production, leading to increased yields, improved resource efficiency, and enhanced resilience against climate change. These systems contribute significantly to sustainable agriculture by optimizing water use, reducing energy consumption, and minimizing environmental footprints.[16]

Boosting agricultural productivity and yields

One of the most direct and significant impacts of AI-powered smart irrigation is the substantial increase in agricultural productivity and crop yields. By precisely delivering water based on real-time needs, these systems eliminate the common problems of over-watering and under-watering, both of which can severely stress crops and reduce output.[17] Studies have consistently shown remarkable improvements:

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I. **Optimized water delivery**: AI algorithms analyse data from soil moisture sensors, weather forecasts, and crop-specific water requirements to determine the optimal amount and timing of irrigation. This precision ensures that plants receive adequate hydration throughout their growth cycle, leading to healthier development and higher yields. For instance, Lakshmipriya et al.[18] demonstrated that AI-based irrigation systems could reduce water usage by up to 50% while maintaining or even improving crop yields.

II. **Reduced plant stress:** Consistent and appropriate water availability minimizes plant stress, which can otherwise lead to stunted growth, reduced fruit/grain development, and increased susceptibility to pests and diseases. By preventing water deficits or excesses, AI systems create an ideal growing environment.

III. **Improved nutrient absorption**: Optimal soil moisture levels facilitate better nutrient uptake by plants. When soil is either too dry or waterlogged, nutrient availability and absorption are compromised. Smart irrigation ensures that nutrients are dissolved and transported effectively to the plant roots, contributing to robust growth.

IV. **Enhanced crop quality:** Beyond just quantity, AI-driven irrigation can also improve the quality of agricultural produce. Consistent water supply at critical growth stages can lead to better fruit size, sugar content, and overall marketability.

In the Nigerian context, where agriculture is predominantly rain-fed and highly vulnerable to erratic rainfall, the adoption of smart irrigation systems offers a crucial pathway to stabilize and boost food production. Akanbi et al.[1] reported a 30% increase in crop yield in Nigeria through the use of AI-powered smart irrigation, alongside a significant reduction in water usage. This demonstrates the direct applicability and positive impact of these technologies in local conditions.

Combating climate change and enhancing resilience

AI-powered smart irrigation systems play a vital role in mitigating the effects of climate change and enhancing the resilience of agricultural systems, particularly in regions like Nigeria that are highly susceptible to climate variability.[19]

I. **Water conservation**: Climate change is leading to increased water scarcity and more frequent droughts in many parts of the world, including Nigeria. Smart irrigation systems are inherently designed for water conservation. By preventing over irrigation and minimizing runoff and deep percolation, they drastically reduce overall water consumption. This is critical for preserving dwindling freshwater resources and ensuring sustainable agricultural practices in a changing climate. Water savings of up to 50% have been observed compared to conventional methods.[20]

II. **Reduced greenhouse gas emissions**: The integration of solar energy into smart irrigation systems significantly reduces the reliance on fossil fuels (e.g., diesel generators) for powering water pumps. This directly translates to a reduction in greenhouse gas (GHG) emissions, contributing to climate change mitigation efforts. By adopting renewable energy sources, agriculture can lessen its carbon footprint and move towards more environmentally friendly practices. The average energy efficiency of solar-integrated systems can range from 85-90%.[20]

III. **Adaptation to erratic weather patterns:** Climate change brings about unpredictable weather patterns, including prolonged dry spells and intense, short bursts of rainfall. AI-powered systems, with their ability to integrate real-time weather data and forecasts, can adapt irrigation schedules dynamically. This adaptability allows farmers to respond effectively to changing conditions, ensuring crops are watered appropriately even during periods of drought or after unexpected rainfall, thereby building resilience against climate shocks.

IV. **Sustainable land management:** By optimizing water use, smart irrigation helps prevent soil degradation issues such as salinization and waterlogging, which can result from inefficient irrigation. This promotes healthier soil ecosystems and contributes to sustainable land management practices, crucial for long-term agricultural viability in the face of climate change.[21]

V. **Enhanced food security:** Ultimately, by boosting yields and making agriculture more resilient to climate impacts, AI powered smart irrigation systems contribute directly to enhanced food security. In a country like Nigeria, where a significant portion of the population faces food insecurity exacerbated by climate change, these technologies offer a powerful tool to ensure a more stable and abundant food supply for a growing population.

In summary, the dual impact of AI-powered smart irrigation systems boosting agricultural production and combating climate change positions them as a critical technology for the future of sustainable agriculture, particularly in vulnerable regions like Nigeria. Their ability to optimize resource use, enhance productivity, and build climate resilience makes them indispensable for achieving food security and environmental sustainability goals.

Challenges and opportunities for implementation in Nigeria

Despite the compelling benefits of AI-powered smart irrigation systems, their widespread adoption and successful implementation in Nigeria face a unique set of challenges. Addressing these hurdles is crucial for unlocking the full potential of these technologies to transform the agricultural sector and enhance climate resilience.

Key challenges

High initial investment costs: The upfront capital expenditure required for AI-powered smart irrigation systems is a significant barrier for many Nigerian farmers, particularly smallholders who constitute the majority of the agricultural workforce. The cost includes not only the sensors, pumps, and automation hardware but also the solar panels, batteries, and charge controllers for sustainable power. Without access to affordable financing options, subsidies, or grants, these technologies remain out of reach for those who could benefit most.[9,22]

I. **Limited access to infrastructure and connectivity**: The effectiveness of IoT-based smart irrigation systems heavily relies on reliable internet connectivity for data transmission to cloud-based AI platforms and for remote monitoring and control. Many rural agricultural areas in Nigeria suffer from inadequate and sporadic internet access, as well as unreliable power supplies. This infrastructure deficit limits the real-time capabilities and overall efficiency of AI solutions.[22]

II. **Lack of technical expertise and awareness**: There is a significant gap in technical knowledge and digital literacy among Nigerian farmers. Many are unfamiliar with AI concepts, IoT devices, and the operation of automated systems. This lack of awareness about the potential benefits and the perceived

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complexity of these technologies can lead to reluctance in adoption. Effective training and capacity-building programs are essential to bridge this knowledge gap.[9,22]

III. **Data management and privacy concerns**: The collection and analysis of vast amounts of agricultural data raise concerns about data ownership, security, and privacy. Farmers may be hesitant to share their farm data without clear policies and regulations ensuring its protection and ethical use. Furthermore, the infrastructure for secure data storage and processing needs to be robust.

IV. **Maintenance and support:** The long-term sustainability of these systems depends on adequate maintenance and technical support. In remote areas, access to skilled technicians for repair and troubleshooting can be limited, and the availability of spare parts may be an issue. This can lead to system downtime and reduced farmer confidence.

V. **Policy and regulatory frameworks**: While there is growing recognition of the importance of sustainable agriculture, specific policy and regulatory frameworks that incentivize and support the adoption of AI-powered smart irrigation systems are still evolving. Clear guidelines, standards, and supportive policies are needed to create an enabling environment for widespread implementation.

Opportunities for advancement

Despite the challenges, several opportunities exist to accelerate the adoption and impact of AI-powered smart irrigation systems in Nigeria:

I. **Government support and incentives:** The Nigerian government's commitment to agricultural development and renewable energy, as outlined in policies like the National Renewable Energy and Energy Efficiency Policy (NREEEP), presents a strong enabling environment. Targeted subsidies, tax breaks, and low-interest loans can significantly reduce the financial burden on farmers and encourage investment in smart farming technologies.[23]

II. **Public-private partnerships (PPPs):** Collaborations between government agencies, private technology firms, financial institutions, and agricultural organizations can facilitate the development and deployment of affordable and context specific AI irrigation solutions. PPPs can also help in establishing training centres and providing technical support services.

III. **Capacity building and extension services**: Investing in comprehensive training programs for farmers, agricultural extension workers, and local technicians is crucial. These programs should focus on practical skills in operating and maintaining smart irrigation systems, as well as understanding the benefits of data-driven farming. Digital literacy initiatives can empower farmers to embrace new technologies.

IV. **Development of localized AI solutions:** Tailoring AI models and system designs to Nigeria's diverse climatic conditions, soil types, and crop varieties can enhance their effectiveness and relevance. Local research institutions and start-ups can play a vital role in developing cost-effective and culturally appropriate solutions that address specific local needs and constraints.

V. **Expansion of rural infrastructure**: Investments in expanding rural internet connectivity (e.g., through satellite internet or community-based networks) and reliable off-grid power solutions (e.g., mini-grids) are fundamental. Improved infrastructure will enhance the functionality and accessibility of smart irrigation systems.

VI. **Awareness campaigns and demonstration farms:** Conducting extensive awareness campaigns and establishing demonstration farms can showcase the tangible benefits of AI-powered smart irrigation to farmers. Seeing successful implementations first-hand can build trust and encourage adoption among skeptical farmers.

VII. **Microfinance and innovative financing models**: Exploring innovative financing models, such as pay-as-you-go systems for solar-powered irrigation or micro-leasing options for equipment, can make these technologies more accessible to smallholder farmers with limited upfront capital.

By strategically addressing the existing challenges and capitalizing on these opportunities, Nigeria can pave the way for a more resilient, productive, and sustainable agricultural sector, effectively harnessing AI-powered smart irrigation systems to combat climate change and ensure food security.

Case studies and implementation examples in Nigeria

While the adoption of AI-powered smart irrigation systems in Nigeria is still in its nascent stages, several initiatives, research projects, and existing agricultural practices provide valuable insights and serve as foundational examples for future widespread implementation. These case studies highlight both the potential and the practical considerations for deploying such advanced technologies in the Nigerian context.

Research and pilot projects

I. **Akanbi et al. (2024) - AI-Powered smart irrigation system and solar energy integration:** This research, directly relevant to the core topic, explored the design and implementation of an AI-powered smart irrigation system integrated with solar energy in Nigeria. Their findings indicated a significant 40% reduction in water usage and a 30% increase in crop yield. The study emphasized the system's effectiveness in optimizing irrigation schedules based on real-time soil moisture and weather data, and the sustainability benefits of solar energy integration. This serves as a strong empirical example of the technology's viability and positive impact in a Nigerian setting.[1]

II. **Sabo et al. (2023) - Solar-powered system with automated irrigation feature:** This study focused on the development of a solar-powered system for soil monitoring with an automated irrigation feature. While not explicitly detailing AI algorithms, the automation aspect driven by sensor data aligns with the principles of smart irrigation. Their work underscores the feasibility of sustainable, automated irrigation solutions in Nigeria, particularly those leveraging renewable energy sources.[7]

III. **Akinpelu and Salisu (2023)** - Feasibility Analysis of AI-Integrated Solar Irrigation Systems: This research investigated the practical feasibility of integrating AI with solar irrigation systems in Nigeria. They found that sensor-based monitoring significantly reduced water wastage while optimizing energy efficiency. Such feasibility studies are crucial for identifying the practical challenges and opportunities for real-world deployment, providing a roadmap for scaling up these technologies.[24]

IV. **Chukwuebuka et al. (2023)** - Real-Time AI-Based Decision Support System for Smart Irrigation in Sub-Saharan Africa:

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Although broader than just Nigeria, this study developed a real-time AI-based decision support system for smart irrigation in sub-Saharan Africa. The principles and technologies explored, such as the use of fuzzy logic controllers for optimal irrigation scheduling, are directly applicable to Nigeria. This highlights the regional relevance and the potential for localized adaptations of such systems.[13]

Existing smart farming initiatives and their relevance

While not always explicitly focused on irrigation, several smart farming initiatives in Nigeria demonstrate the growing adoption of technology in agriculture, providing a foundation for integrating AI-powered irrigation:

I. **Babban gona:** This commercial farming organization in Nigeria integrates technology to assist smallholder farmers. While their primary focus has been on providing access to credit, quality inputs, and training, their use of mobile technologies and analytics to provide useful recommendations to farmers on maximizing crop productivity aligns with the data-driven approach of smart agriculture. Their model demonstrates how technology can be leveraged to improve profitability and income for smallholders.[22]

II. **Application of IoT and AI in precision farming (Nwosu and Adewale, 2023):** This research examined the broader application of IoT and AI in precision farming within a Nigerian context. They found that automated irrigation systems improved efficiency by minimizing overwatering and soil nutrient depletion. This indicates a general trend towards precision agriculture, of which smart irrigation is a key component.[25]

III. **Use of drones for farm monitoring and security:** as highlighted by Falana et al. (2024), drones equipped with AI capabilities are increasingly being used for agricultural property patrols, aerial monitoring, and even for identifying crop health issues. While primarily for security and monitoring, the data collected by these drones can be integrated into smart irrigation systems to provide additional insights for water management decisions.[22]

Lessons learned and future directions from case studies

The existing case studies and initiatives, though limited in number for comprehensive AI-powered smart irrigation, offer several critical lessons:

I. **Demonstrated efficacy:** The research projects clearly demonstrate the technical viability and significant benefits (water savings, yield increase) of AI-powered solar irrigation systems in Nigeria.

II. **Importance of solar integration:** The success of these projects often hinges on the integration of solar energy, addressing the critical challenge of unreliable power supply in rural areas.

III. **Need for localized solutions:** The diverse agro-ecological zones in Nigeria necessitate localized AI models and system designs that are tailored to specific soil types, crop varieties, and climatic conditions.

IV. **Bridging the knowledge gap:** The success of initiatives like Babban Gona in technology adoption among smallholders suggests that effective training, extension services, and simplified user interfaces are crucial for overcoming the lack of technical expertise.

V. **Scalability challenges:** While pilot projects show promise, scaling up these solutions across the vast agricultural landscape of Nigeria requires addressing the high initial costs and infrastructure deficits. Innovative financing models and public private partnerships will be key.

These case studies, though a starting point, provide a strong foundation for understanding the practical implications and potential of AI-powered smart irrigation in Nigeria. They underscore the need for continued research, pilot projects, and strategic investments to transition from isolated successes to widespread adoption, ultimately contributing to a more food-secure and climate-resilient agricultural sector.

Policy recommendations and future outlook

The successful and widespread adoption of AI-powered smart irrigation systems in Nigeria hinges not only on technological advancements but also on supportive policy frameworks and a forward-looking strategic outlook. To fully harness the potential of these systems for boosting agricultural production and combating climate change, a multi-pronged approach involving government, private sector, and research institutions is essential.

Policy recommendations

To create an enabling environment for the proliferation of AI-powered smart irrigation, the following policy recommendations are crucial:

Develop a national smart agriculture policy: The Nigerian government should formulate a comprehensive national policy specifically dedicated to smart agriculture, with a strong emphasis on AI-powered irrigation. This policy should outline clear objectives, targets, and strategies for technology adoption, infrastructure development, and capacity building. It should integrate with existing agricultural and climate change adaptation policies.

Provide financial incentives and subsidies: To mitigate the high initial investment costs, the government should introduce targeted financial incentives. These could include:

I. **Subsidies:** Direct subsidies for the purchase of AI-powered irrigation equipment, solar panels, and related components.

II. **Low-interest loans:** Facilitate access to low-interest loans through agricultural banks and microfinance institutions, specifically for smart farming technologies.

III. **Tax breaks:** Offer tax exemptions or reductions for companies manufacturing, importing, or deploying smart irrigation systems, and for farmers adopting these technologies.

Invest in rural infrastructure development: Prioritize investment in reliable rural internet connectivity and stable power supply. This could involve expanding broadband infrastructure, promoting community-based Wi-Fi initiatives, and supporting the deployment of decentralized renewable energy solutions (e.g., mini-grids) in agricultural areas.

Strengthen research and development (R&D): Increase funding for agricultural research institutions and universities to conduct R&D on localized AI models and cost-effective smart irrigation solutions tailored to Nigeria's diverse agro-ecological zones. Encourage public-private partnerships in R&D to accelerate innovation and technology transfer.

Establish comprehensive training and extension programs: Develop and implement nationwide training programs for farmers,

agricultural extension agents, and local technicians. These programs should focus on practical skills for operating, maintaining, and troubleshooting AI-powered irrigation systems, as well as fostering digital literacy and data-driven decision-making.

Create data governance frameworks: Develop clear policies and regulations regarding agricultural data collection, ownership, privacy, and sharing. This will build trust among farmers and encourage data sharing, which is vital for training and improving AI models. Ensure data security and ethical use of AI in agriculture.

Promote public-private partnerships (PPPs): Foster collaborations between government, technology providers, financial institutions, and farmer cooperatives. PPPs can drive innovation, facilitate technology transfer, provide financing, and ensure the sustainable deployment and maintenance of smart irrigation systems.

Future outlook

The future of AI-powered smart irrigation in Nigeria is promising, with several key trends and advancements expected to shape its trajectory:

I. **Increased integration of diverse data sources:** Future systems will likely integrate an even wider array of data, including satellite imagery, drone-based hyperspectral data, weather station networks, and even genomic data of crops. This will enable more holistic and precise decision-making, moving beyond just water management to integrated farm management.

II. **Edge computing and decentralized AI:** To overcome connectivity challenges in remote areas, there will be a growing trend towards edge computing, where AI processing occurs closer to the data source (e.g., on the farm itself) rather than relying solely on cloud infrastructure. This will reduce latency and dependence on constant internet access.

III. **Advanced AI models and robotics:** The development of more sophisticated AI models, including reinforcement learning and explainable AI (XAI), will lead to even more adaptive and transparent irrigation decisions. Robotics and autonomous farm machinery could integrate seamlessly with AI irrigation systems for fully automated planting, monitoring, and harvesting.

IV. **Climate-smart agriculture hubs**: The establishment of regional climate-smart agriculture hubs could serve as centres for research, demonstration, training, and technology dissemination. These hubs would showcase AI-powered irrigation alongside other climate-resilient farming practices.

V. **Circular economy integration:** Future systems might integrate more closely with waste management and nutrient recycling, for instance, by optimizing the use of treated wastewater for irrigation or precisely applying organic fertilizers based on AI-driven soil analysis.

VI. **Policy and investment growth:** As the benefits become more evident and the urgency of climate change intensifies, there will likely be increased policy support and investment from both domestic and international sources, accelerating the adoption rate.

By proactively addressing policy gaps, investing in infrastructure and human capital, and fostering innovation, Nigeria can position itself as a leader in climate-smart agriculture, leveraging AI-powered smart irrigation systems to ensure food security, economic prosperity, and environmental sustainability for future generations.[26,27]

Conflicts of interest

The author declares there is no conflict of interest.

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