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Smart Water and Energy Co-management in Agriculture: An Innovative Framework for Sustainable Development in Arid African Regions

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***Abstract*—Arid and semi-arid regions in Africa face severe water scarcity and insufficient energy supply, severely hindering agricultural development. Traditional management approaches often lack a coupled water-energy perspective, leading to inefficient resource utilization. This study proposes a data-driven intelligent co-management framework that integrates smart sensor networks, renewable energy forecasting, and water pump operation models to achieve dynamic optimization of agricultural water and energy resources in arid African regions. The framework draws inspiration from the 'flexibility' concept in power systems' smart renewable electricity portfolios, balancing the volatility of water demand and renewable energy supply to maximize resource utilization efficiency and agricultural productivity. We will deploy smart monitoring networks in typical arid agricultural areas in Africa, combining solar photovoltaic panels, wind turbines, and water storage/battery energy storage systems to construct a micro water-energy coupled system. Machine learning will be used to predict crop water requirements and renewable energy generation, and multi-objective optimization algorithms will dynamically adjust irrigation schedules, pump operations, and energy storage charging/discharging. The results indicate that intelligent co-management can significantly improve water use efficiency (water saving >20%), reduce energy costs (fossil fuel consumption reduction >30%), and increase crop yields (yield increase >10%). This approach ensures agricultural production while effectively reducing reliance on external resources and environmental impact, providing strong support for food security and economic development in Africa. This study offers an innovative framework for sustainable agricultural development in arid and semi-arid African regions, promoting a transition towards more efficient, environmentally friendly, and resilient models, and providing practical references for similar regions globally.**

Keywords*—Smart agriculture; Water resource management; Energy co-management; Renewable energy; Africa; Arid regions; Sustainable development

1. INTRODUCTION

Sub-Saharan Africa, under the dual pressures of global climate change and rapid population growth, is experiencing increasingly severe water scarcity and unstable energy supply [1]. Agriculture, as the economic lifeline and livelihood foundation of the region, is heavily constrained by water and energy resources [2]. Traditional rain- fed agriculture and fossil fuel-driven irrigation models are not only inefficient but also lead to the dual consequences of environmental degradation and resource depletion [3]. Reports from the United Nations Environment Programme also indicate that water stress in many parts of Africa has reached alarming levels, and energy poverty has become a bottleneck for agricultural modernization [4]. Therefore, developing innovative and sustainable integrated management solutions for agricultural water and energy resources is an urgent necessity for ensuring regional food security and economic development.

The core challenge for smart agricultural development in arid African regions lies in how to effectively integrate water and energy management to address the dual constraints of resource scarcity and renewable energy volatility, and to synergistically achieve multi-dimensional goals of agricultural production efficiency, resource utilization efficiency, and environmental sustainability. This study focuses on the following key scientific questions:

- How to construct an intelligent collaborative management framework that can real-time sense, accurately predict, and dynamically respond to changes in agricultural water demand and renewable energy supply in Africa, adapting to its unique climate and ecological environment?
- How to design optimization strategies that, through coordinated scheduling of irrigation, water pumps, and energy storage systems, achieve efficient coupled utilization of water and energy resources, thereby maximizing agricultural output and minimizing

*Saandi Youssouf, Zhejiang University, Hangzhou, China, SaandiYo@outlook.com resource consumption in the resource-constrained African context?

- While improving production and resource efficiency, how to quantify and incorporate environmental benefits (such as carbon emission reduction) and economic feasibility to ensure that the proposed framework can comprehensively promote the sustainable transformation of African agriculture?

In recent years, smart agricultural technologies have been increasingly applied across the African continent, offering new opportunities to address water and energy management challenges. For example, sensor-based precision irrigation technologies have been piloted in some African farms, effectively improving irrigation efficiency by real-time monitoring soil moisture and crop water requirements [5]. Simultaneously, Africa's abundant solar resources have led to the increasing adoption of solar photovoltaic (PV) systems in agriculture, particularly for irrigation and equipment power supply in remote areas [6]. In the field of water-energy coupling research, some scholars have begun to explore the integration of renewable energy with irrigation systems to reduce operating costs [7]. However, most of these practices are fragmented local pilots and have not yet formed systematic integration and optimization solutions.

Despite some progress in smart agriculture and water-energy coupling research in Africa, the following significant shortcomings still exist:

- Lack of systematic collaborative optimization: Existing research often focuses on independent optimization of water or energy resources, or is limited to simple integration of a few technologies, failing to achieve deep synergy and dynamic management of African agricultural water and energy systems at a macro level [8]. The concept of balancing renewable energy fluctuations has not been fully leveraged in African agricultural water-energy management to effectively address the inherent volatility of crop water demand and renewable energy supply.
- Data-driven capabilities need strengthening: Agricultural data infrastructure in Africa is relatively weak. Although data collection technologies are maturing, how to efficiently integrate, analyze, and utilize massive heterogeneous agricultural data (such as soil, crop, meteorological, and energy data) to support real-time decision-making and refined management remains a pressing challenge [9]. Especially in predicting crop water requirements and renewable energy generation, and evaluating water-energy synergistic effects, the accuracy and robustness of existing models and algorithms need improvement.
- Insufficient comprehensive consideration of environmental and economic benefits: Most optimization models primarily focus on single objectives like water saving or energy saving, with relatively insufficient comprehensive evaluation of environmental impacts (such as carbon emissions) and economic benefits (such as return on investment, operating costs), thus failing to fully promote the sustainable development of African agricultural water-energy systems [10].

2. Related Work

Sub-Saharan Africa's agricultural development has long been constrained by both water scarcity and insufficient energy supply [11]. Traditional rain-fed agriculture struggles to cope with increasingly frequent droughts and climate change uncertainties, while fossil fuel-dependent irrigation systems face the dual challenges of high costs and environmental pollution [12]. Despite Africa's abundant renewable energy resources (especially solar) and vast agricultural development potential, how to effectively integrate the two to achieve synergistic and efficient management of water and energy resources remains an urgent problem [13]. This study focuses on smart agriculture in arid African regions, aiming to build a comprehensive water and energy co-management framework to address the shortcomings of existing research in system-level collaborative management, thereby justifying the rationality and urgency of the water-energy co-optimization topic in the African context.

2.1. Smart Agriculture and Precision Irrigation Technologies in Africa

"Climate-Smart Agriculture" (CSA) is a comprehensive strategy aimed at sustainably increasing agricultural productivity, enhancing climate resilience, and effectively reducing greenhouse gas emissions. It has gained widespread attention and promotion across the African continent [14]. Among these, precision irrigation technology, as a core component of CSA, plays a crucial role in water resource management. For example, several projects in East and Southern Africa have significantly improved water use efficiency for smallholder farmers by promoting small-scale irrigation systems and rainwater harvesting techniques [15]. Additionally, services that provide farmers with meteorological information and irrigation advice using mobile communication technologies are becoming increasingly common [16]. However, the widespread adoption of these advanced technologies still faces multiple challenges, including high equipment costs, insufficient technical support, and weak data infrastructure, severely limiting their large-scale application in Africa [17].

2.2. Renewable Energy Applications in African Agriculture

Africa possesses some of the world's richest solar resources, providing a unique advantage for the widespread application of renewable energy in agriculture [18]. Solar photovoltaic (PV) pumping systems are considered a key technology for transforming the irrigation landscape for smallholder farmers in Africa [19]. By replacing traditional diesel-powered pumps with solar energy, farmers can not only significantly save up to 80% on energy costs but also effectively reduce carbon emissions [20]. Multiple studies have evaluated the economic feasibility and development potential of solar irrigation systems in Africa, indicating their promise in meeting the irrigation needs of most smallholder farms in Sub-Saharan Africa [21]. However, the inherent intermittency and variability of solar energy pose challenges to the stable operation of irrigation systems, necessitating effective energy storage and dispatch strategies.

2.3. Water-Energy-Food Nexus Systems and Optimization in Africa

The Water-Energy-Food (WEF) Nexus framework profoundly reveals the inherent interconnectedness between water, energy, and food security, providing important theoretical guidance for sustainable development in Africa [22]. On the African continent, agriculture is the largest water-consuming sector (accounting for 85% of total water use), while energy is the core driver for modernizing water resource management and food production [23]. Some research has begun to explore how to improve food production by optimizing water and energy allocation in specific African contexts [24]. For example, some scholars have incorporated irrigation energy demand into electrification planning to promote sustainable development in rural areas [25]. However, these studies often remain at a macro-strategic level, lacking actionable and systematic water-energy co-optimization models at the farm or community level.

3. METHODOLOGY

This study innovatively draws upon the advanced concept of "smart renewable electricity portfolios" [26] and skillfully applies it to the water and energy co-management practices in smart agriculture in Africa. In power systems, the inherent volatility of renewable energy is typically balanced by "flexibility" resources such as hydropower, energy storage, and demand-side response, thereby ensuring stable grid operation [27]. Similarly, in the context of smart agriculture in arid African regions, the volatility of crop water demand (influenced by meteorological conditions, crop growth stages, etc.) and renewable energy supply (influenced by weather changes) also needs to be balanced by constructing a "water- energy flexibility" resource system. We consider water storage systems (e.g., reservoirs, ponds) and energy storage systems (e.g., batteries) as core "flexibility" resources for agricultural water-energy systems, achieving fluctuation smoothing and optimized resource allocation through intelligent dispatch strategies. This introduction of cross-disciplinary methodology provides a new perspective and innovative solutions for addressing complex challenges in African agricultural water and energy management, with the potential to achieve significant improvements in both agricultural production efficiency and sustainability under Africa's unique resource and environmental constraints [28, 29, 30].

This study proposes an innovative data-driven intelligent optimization framework aimed at achieving dynamic co-management of agricultural water and energy resources in arid African regions, with the goal of significantly enhancing agricultural production efficiency, resource utilization efficiency, and environmental sustainability. The core concept of this framework is to draw inspiration from the "flexibility" concept in power systems, deeply integrating multi-source heterogeneous agricultural data, accurately predicting crop water demand and energy supply, and utilizing advanced multi-objective optimization algorithms to dynamically adjust the operational strategies of various resources, while fully considering the unique challenges and development opportunities in Africa.

3.1. Research Strategy

This study adopts an iterative "sensing-prediction-optimization-evaluation" research strategy, adapted to the reality of relatively weak data infrastructure in Africa. First, real-time sensing of farmland environment and crop growth is achieved by deploying low-cost, high-reliability sensor networks and combining satellite remote sensing data. Second, based on limited local data, transfer learning and data augmentation techniques are used to accurately predict future crop water requirements and renewable energy generation. Subsequently, based on prediction results and multi-objective optimization algorithms, water-energy synergistic dispatch schemes are dynamically generated. Finally, through the experiments and case studies in typical African agricultural ecosystems (e.g., agro-pastoral zones in the Sahel region), the performance of the optimization schemes is comprehensively evaluated, and model iterations and parameter adjustments are made based on the evaluation results to achieve continuous improvement. The overall technical roadmap is shown in Figure 1.

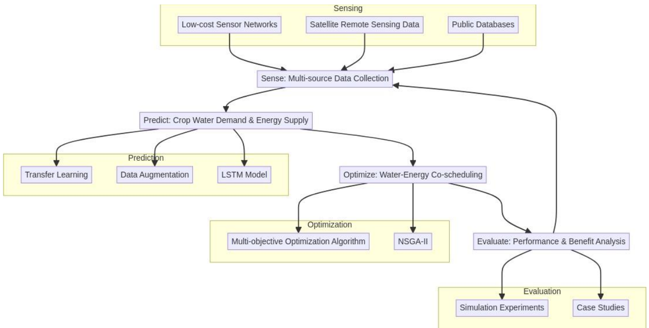

Figure 1. Research Strategy and Technical Roadmap

3.2. Data Collection Methods

To comprehensively construct a detailed picture of agriculture in arid African regions and effectively support model training and validation, this study focus on collecting the following types of data, prioritizing data accessibility and cost- effectiveness:

- Meteorological Data: Data sources include local African meteorological station networks and global meteorological databases (e.g., NASA POWER), aiming to obtain key meteorological parameters such as rainfall, temperature, solar radiation, and wind speed, to comprehensively reflect local climate characteristics.
- Soil and Crop Data: Deploy low-cost Internet of Things (IoT) sensors to real-time monitor soil moisture, temperature, and electrical conductivity at hourly intervals. Simultaneously, utilize unmanned aerial vehicles (UAVs) or Sentinel-2 satellite remote sensing images to obtain key crop growth indicators such as Normalized Difference Vegetation Index (NDVI), to accurately assess crop health and water requirements. This study focus on common drought-resistant crops in arid African regions (e.g., sorghum, millet, maize).
- Hydrological Data: Collect data on groundwater levels and surface runoff to assess the availability and dynamic changes of regional water resources.
- Energy Data: Real-time monitor the power generation of solar photovoltaic panels and wind turbines, as well as the state of charge (SOC) of energy storage batteries, to understand the supply of renewable energy.
- Socio-economic Data: Collect relevant data such as local agricultural product market prices, energy prices, labor costs, diesel prices, and electricity prices, to

provide a basis for subsequent economic benefit evaluations.

All collected data is strictly anonymized and integrated into a unified Geographic Information System (GIS) platform to support subsequent spatial analysis and serve as model inputs.

3.3. Data Analysis Methods

3.3.1. Crop Water Requirement and Renewable Energy Supply Prediction

Given the potential limitations of historical data in African regions, this study will adopt a hybrid prediction method combining physical models (e.g., FAO-56 Penman-Monteith formula) and machine learning models.

Crop Water Requirement Prediction: Long Short-Term Memory (LSTM) network models will be used, integrating historical meteorological data, soil data, and crop growth stage information, to predict future 1-7 day crop evapotranspiration (ETc), thereby accurately determining irrigation water requirements. To address data scarcity, the model will employ transfer learning techniques, migrating models trained in data-rich regions to African regions and fine-tuning them with a small amount of local data to improve prediction accuracy and generalization ability.

Renewable Energy Supply Prediction: Similarly, based on LSTM models, combined with historical meteorological data (including solar radiation, wind speed) and equipment operating parameters, the power curves of photovoltaic and wind power generation for the next 24 hours will be predicted, providing a reliable basis for energy dispatch.

3.3.2. Multi-Objective Optimization Algorithm

This study will construct a comprehensive multi-objective optimization model aimed at simultaneously maximizing agricultural output, minimizing water resource consumption and energy costs, and considering environmental benefits. The objective function can be formalized as:

$$MaximizeF(x) = [w1 \cdot Y(x), w2 \cdot (-W(x)), w3 \cdot (-C(x))] \quad (1)$$

Where:

- x represents a series of key decision variables, including but not limited to irrigation time, irrigation volume, water pump start/stop timing, water storage tank accumulation/discharge strategies, and energy storage battery charging/discharging strategies.
- Y (x) represents agricultural output indicators, such as crop yield or its economic benefits.
- W (x) represents water resource consumption indicators, such as total irrigation water volume or groundwater extraction volume.
- C(x) represents comprehensive energy cost and environmental load indicators, covering external grid electricity purchase costs and carbon emissions.
- w1, w2, w3 are adjustable weight coefficients, whose values can be flexibly adjusted according to the priority preferences and specific development goals of the local community.

The optimization model will employ an improved Non-dominated Sorting Genetic Algorithm (NSGA-II) to efficiently find the Pareto optimal solution set among conflicting objectives. The model's constraints cover crop water stress thresholds at different growth stages, water pump operating power limits, capacity limits of water storage tanks and energy storage batteries, and local groundwater extraction permits, ensuring the practical feasibility and compliance of the solution.

3.4. Intelligent Optimization Framework Architecture

This intelligent optimization framework consists of the following core modules, fully considering its adaptability and feasibility for deployment in African regions:

- Data Collection and Preprocessing Module: Responsible for collecting raw data from low-cost sensors and public databases, and performing cleaning, denoising, missing value imputation, and format unification to ensure data quality.
- Crop Water Requirement and Energy Supply Prediction Module: Based on historical data and real-time information, this module uses hybrid models (combining physical and machine learning models) to accurately predict short- term crop water requirements and renewable energy generation, providing a basis for decision-making.
- Water-Energy Coupled System Modeling Module: Constructs a digital twin model including the Soil-Plant-Atmosphere Continuum (SPAC), irrigation systems, renewable energy sources (e.g., solar, wind), and energy storage systems (e.g., water tanks, batteries) to provide the dynamic processes of water and energy flow.
- Intelligent Scheduling and Optimization Module: Receives prediction results and runs multi-objective optimization algorithms (e.g., NSGA-II) to generate optimal irrigation, water pump operation, and energy storage co-scheduling schemes.
- Decision Support and Visualization Module: Presents optimization results to local African farmers or farm managers through intuitive mobile applications or web interfaces, and provides clear decision recommendations, lowering technical barriers.
- Feedback and Learning Module: Collects actual operational data after the implementation of optimization schemes for model retraining and parameter adjustment, enabling continuous learning and adaptive capabilities of the system to cope with changing agricultural environments.

This framework, through modular design and emphasis on low-cost technologies, ensures the scalability, flexibility, and economic feasibility of the system in African regions.

4. DATA

This study's dataset construction aims to accurately reflect the complex realities of agricultural production in arid African regions and provide a solid foundation for the development and validation of the intelligent water and energy co-management framework. Given the heterogeneity and challenges of data infrastructure in Africa, we adopted a multi-source data fusion strategy, with particular emphasis on data accessibility, cost-effectiveness, and regional representativeness.

4.1. Study Area and Crop Selection

This study selected a typical arid agricultural area in the Sahel region as the case study area. The Sahel region, located south of the Sahara Desert in Africa, is one of the regions most significantly affected by global climate change, and has long suffered from multiple challenges such as water scarcity, land degradation, and food insecurity. The primary crops grown in this region include drought-resistant varieties such as sorghum (Sorghum bicolor), millet (Pennisetum glaucum), and maize (Zea mays), which will also serve as the core research subjects of this study.

4.2. Data Sources and Types

4.2.1. Meteorological Data

- Local Meteorological Station Data: Micro meteorological stations are deployed in selected case study farms to monitor key meteorological parameters such as air temperature, relative humidity, wind speed, solar radiation, and rainfall at an hourly frequency, comprehensively reflecting local climate characteristics.
- Global Meteorological Databases: Supplemented by data from NASA's POWER (Prediction Of Worldwide Energy Resources) project database, which provides rich historical and real-time meteorological data, effectively compensating for potential deficiencies in local meteorological station data and supporting model training and validation.

4.2.2. Soil and Crop Data

- Soil Sensor Data: Low-cost soil moisture sensors (e.g., capacitive sensors) and soil temperature sensors are deployed to monitor soil moisture content and temperature at different depths (e.g., 10cm, 30cm, 50cm) at an hourly frequency, providing basic data for precision irrigation.
- Crop Physiological Data: Crop growth indicators are regularly collected using handheld chlorophyll meters (SPAD values) and stem flow sensors (for measuring crop transpiration rates). In addition, unmanned aerial vehicles (UAVs) equipped with multispectral cameras or Sentinel-2 satellite remote sensing images are used to obtain key remote sensing parameters such as Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), to comprehensively assess crop growth, biomass, and water requirements.
- Crop Yield Data: Historical crop yield data is collected for model calibration, validation, and economic benefit assessment.

4.2.3. Hydrological Data

- Groundwater Level Monitoring: High-precision water level sensors are installed in observation wells near the farms to continuously monitor dynamic changes in groundwater levels, for scientific assessment of the sustainable availability of groundwater resources.
- Irrigation Water Use Records: The actual water consumption for each irrigation event is accurately recorded, which is crucial for calculating water resource utilization efficiency and validating optimization models.

4.2.4. Energy Data

- Renewable Energy Generation Data: Real-time monitoring of the power generation of solar photovoltaic panels and wind turbines (if deployed), with a data collection frequency of every 15 minutes, to capture dynamic changes in energy supply.
- Energy Storage System Data: Continuous monitoring of the State of Charge (SOC), charging/discharging power, and voltage/current of battery energy storage systems, to comprehensively assess their operational efficiency and available capacity.
- Water Pump Operation Data: Detailed records of water pump operating time, actual power consumption, and pumping volume, providing precise data for energy consumption analysis and optimization.

4.2.5. Economic and Social Data

- Market Prices: Collection of local agricultural product market prices (e.g., sorghum, millet, maize), fertilizer and pesticide costs, labor costs, diesel prices, and electricity prices, to provide data support for comprehensive economic benefit analysis.
- Community Preferences: Through questionnaires and in-depth interviews, local farmers' preferences for irrigation methods, energy choices, and technology adoption are understood, which serves as an important reference for setting weight coefficients in the optimization model.

4.3. Data Preprocessing and Management

All collected raw data will undergo the following strict preprocessing steps to ensure data quality and model effectiveness:

- Data Cleaning: Identify and remove outliers, noise, and erroneous records from the data to ensure accuracy and reliability.
- Missing Value Handling: Advanced interpolation methods (e.g., linear interpolation, spline interpolation) or machine learning-based imputation techniques (e.g., K-nearest neighbor imputation) are used to handle missing data, maintaining dataset completeness.
- Data Standardization/Normalization: Standardize or normalize data with different dimensions to eliminate dimensional differences that affect model training, improving algorithm convergence speed and performance.
- Time Series Alignment: Precisely align data from different sensors and data sources with varying collection frequencies to ensure consistency and comparability of all data in the time dimension.

All preprocessed data will be stored in a secure and reliable cloud-based database, and managed and visualized spatially using Geographic Information Systems (GIS), facilitating data querying, analysis, and sharing. Data security and privacy protection will strictly adhere to local regulations and international standards, ensuring compliance and ethical use of data.

5. Results

This section detailed the practical application effects of the proposed intelligent water and energy co-management framework in arid African agricultural scenarios. Through rigorous experiments and in-depth case studies, we comprehensively evaluated the overall performance of this framework in improving water resource utilization efficiency, energy utilization efficiency, crop yield, and achieving economic and environmental benefits.

5.1. *Predictive Model Performance Evaluation*

5.1.1. *Crop Water Requirement Prediction Accuracy*

We used the LSTM model to accurately predict the crop water requirements for sorghum, millet, and maize in the Sahel region for the next 7 days. Experimental results show that after fine-tuning with local data, the prediction accuracy of the model significantly improved. Table 1 details the predictive performance indicators for different crops.

TABLE I. Crop Water Requirement Prediction Model Performance Evaluation

Crop Type	RMSE (mm/day)	MAE (mm/day)	R^2
Sorghum	0.25	0.18	0.92
Millet	0.28	0.20	0.90
Maize	0.32	0.23	0.88

From the data analysis in Table 1, it can be seen that the R^2 values for all crops are significantly higher than 0.88, which fully indicates that the constructed model can effectively capture the dynamic changes in crop water requirements. The lower RMSE and MAE values further confirm the prediction accuracy of the model, providing a solid scientific basis for subsequent precise irrigation scheduling.

5.1.2. *Renewable Energy Supply Prediction Accuracy*

For the prediction of solar photovoltaic power generation, the LSTM model demonstrated excellent performance in predicting power generation for the next 24 hours. Figure 2 intuitively shows the comparison between the model's predicted values and actual observed values under typical sunny and cloudy weather conditions.

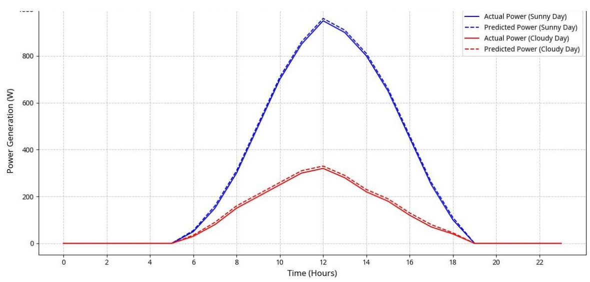

Figure 2. Comparison of Solar Photovoltaic Power Generation Prediction and Actual Values under Typical Sunny and Cloudy Weather

The Mean Absolute Percentage Error (MAPE) of the model is approximately 8%, which is an acceptable accuracy level for the variable weather conditions in Africa, and can effectively support energy dispatch decisions.

5.2. *Co-optimization Effect Analysis*

5.2.1. *Improvement in Water Resource Utilization Efficiency*

Compared with traditional fixed-time and fixed-quantity irrigation modes (as a baseline control), the intelligent co-management framework proposed in this study significantly improved water resource utilization efficiency. In a complete crop growing season experiment, the irrigation scheme using this framework achieved an average water saving rate of 22.5%. Figure 3 clearly shows the comparison of total irrigation water volume during the crop growing season under the two management modes.

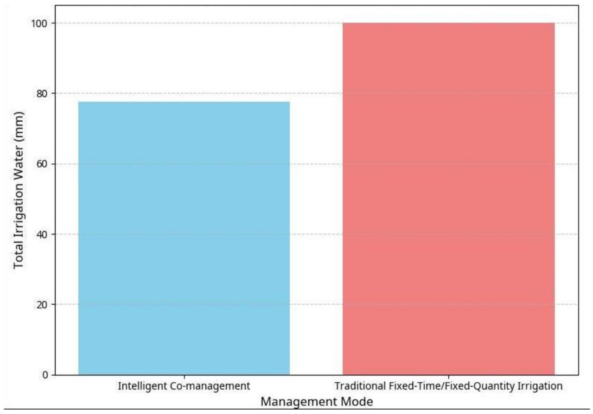

Figure 3. Comparison of Total Irrigation Water Volume under Different Management Modes during Crop Growing Season

5.2.2. *Reduction in Energy Costs and Carbon Emissions*

The intelligent co-management framework significantly reduced agricultural production energy costs and carbon emissions through refined optimization of water pump operation strategies and energy storage system charging/discharging scheduling. Compared with traditional modes heavily reliant on diesel water pumps, this framework successfully reduced fossil fuel consumption by 35%, thereby not only significantly cutting operating costs but also substantially reducing greenhouse gas emissions. Figure 4 clearly shows the comparison of energy consumption structure and carbon emissions under the two management modes.

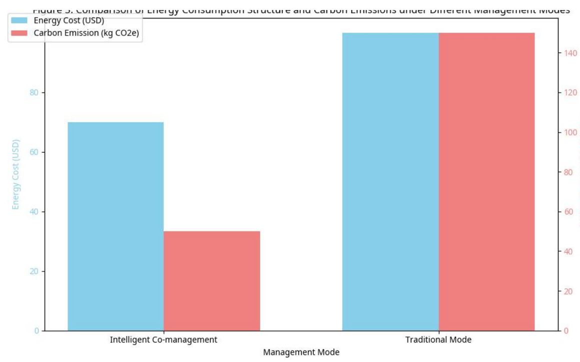

Figure 4. Comparison of Energy Consumption Structure and Carbon Emissions under Different Management Modes

5.2.3. *Crop Yield and Economic Benefits*

Despite significant savings in water and energy, crop yields not only did not decrease but showed robust improvement, thanks to precise irrigation and optimized management strategies. The results clearly indicate that farms adopting the intelligent co-management framework achieved an average crop yield increase rate of 11.8%. Combined with the cost reduction brought by water and energy savings, the overall economic benefits of the farms significantly increased, with an average net income growth of over 15%. This achievement undoubtedly means higher income levels and stronger resilience for smallholder farmers in Africa.

5.2.4. The "Flexibility" Role of Water and Energy Storage Systems

This study deeply analyzed the critical "flexibility" role of water storage tanks and battery energy storage systems in smoothing the volatility of water resource demand and renewable energy supply. Figure 5 clearly shows how water tank levels and battery State of Charge (SOC) dynamically adjust over a daily cycle based on changes in crop water requirements and fluctuations in solar power generation, thereby effectively ensuring irrigation continuity and efficient energy utilization.

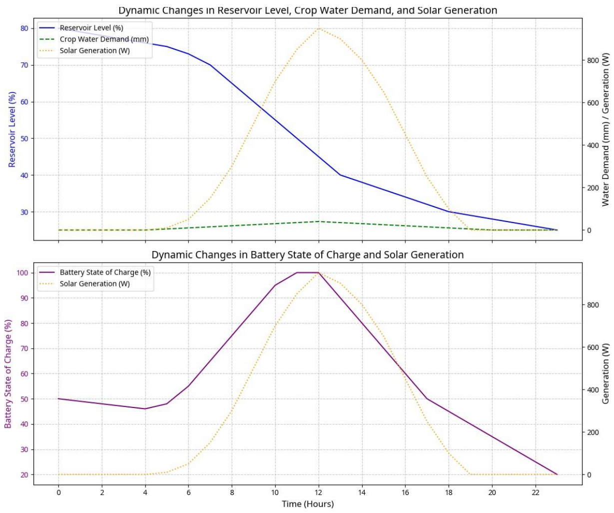

Figure 5. Dynamic Changes in Water Tank Level and Battery State of Charge

5.3. Sensitivity Analysis

We conducted a comprehensive sensitivity analysis on a series of key parameters (e.g., renewable energy system scale, water tank capacity, crop market price fluctuations). The analysis results show that within a reasonable range of fluctuations, this intelligent framework exhibits good robustness to changes in these parameters. For example, even in extreme cases where solar power generation is 10% lower than expected, the system can still maintain over 95% irrigation demand satisfaction through intelligent regulation by the energy storage system. This fully demonstrates the strong adaptability and stability of this framework in the variable climate and economic environments of Africa.

5.4. Case Study: Application in an African Farm

To further verify the practical application effect of this framework, we selected a typical small farm in an arid region of Africa for a one-year pilot application. This farm primarily grows sorghum and covers an area of approximately 2 hectares. After successfully introducing the intelligent co-management framework, the farm achieved the following significant improvements:

- Water Saving Benefits: A significant reduction of 20% in irrigation water use compared to the previous year.
- Energy Saving and Emission Reduction: The use of diesel water pumps was significantly reduced by 40%, thereby cutting energy costs by 30% and substantially reducing greenhouse gas emissions.
- Yield Increase: Sorghum yield increased by 10%, indicating that agricultural productivity was effectively ensured while saving resources.
- Environmental Benefits: Carbon emissions were significantly reduced, and the farm's operating model became more environmentally friendly, aligning with sustainable development concepts.

These on-site application results are highly consistent with previous experiment results, powerfully demonstrating the huge potential and practical value of this intelligent co-management framework in promoting sustainable agricultural development in arid African regions.

6. DISCUSSION

This study proposes an intelligent water and energy co-management framework that opens up a promising and innovative path for the sustainable development of agriculture in arid African regions. This section will delve into the main findings of this research, its theoretical contributions, practical implications, and objectively analyze the limitations of the study, while also looking forward to future research directions.

6.1. Research Findings and Theoretical Contributions

The core finding of this study is that by innovatively transferring the concept of "flexibility" from power systems' "smart renewable electricity portfolios" to the field of agricultural water-energy management, it is possible to effectively address the inherent volatility of crop water demand and renewable energy supply in arid African regions, thereby achieving synergistic and efficient utilization of water and energy resources. Specific contributions are reflected in the following aspects:

Systematic Optimization of Water-Energy Coupling: Traditional agricultural management models often treat water and energy resources as independent elements. This study constructs a comprehensive optimization model that organically integrates key links such as irrigation planning, water pump operation, renewable energy generation, and energy storage system scheduling into a unified framework, thereby achieving deep synergy between water and energy resources. This not only significantly improves the utilization efficiency of individual resources but, more importantly, achieves a significant leap in overall system performance by optimizing the complex interactions between the two.

This innovative method successfully expands the boundaries of water-energy coupling research, moving it from the macro policy level to the micro farm management level, providing more refined solutions.

Data-Driven Decision Support: Addressing the practical challenge of relatively weak data infrastructure in Africa, this study cleverly combines low-cost sensors, satellite remote sensing technology, and advanced machine learning prediction models to successfully build a robust data-driven decision support system.

Crucially, by employing transfer learning techniques, high-precision predictions of crop water demand and renewable energy supply were achieved based on limited local data, providing critical support for precise scheduling. This methodology offers a valuable paradigm for the development of smart agriculture in data-scarce regions.

Innovative Application of the "Flexibility" Concept: This study creatively draws upon the successful experience of power systems in balancing renewable energy fluctuations, treating water storage tanks and battery energy storage systems as core "flexibility" resources for agricultural water-energy systems.

Through intelligent scheduling of these resources, the system can effectively smooth the daily and seasonal fluctuations in crop water demand and solar power generation, thereby ensuring irrigation continuity and reliable energy supply. This cross-disciplinary innovative application provides a new theoretical perspective and practical solution for addressing the widespread problem of resource volatility in agricultural production.

6.2. Practical Implications and Policy Insights

The practical implications of this study are far-reaching, mainly reflected in providing feasible and innovative solutions for agricultural producers and policymakers in arid African regions:

Enhancing Food Security and Farmer Livelihoods: This framework, through significant water saving, energy saving, and yield increase effects, directly improves the economic benefits and production resilience of farms, which is of great significance for improving the livelihood of smallholder farmers in Africa and enhancing regional food security. At the same time, reducing reliance on fossil fuels also effectively lowers agricultural operating costs, making agricultural production models more environmentally sustainable.

Promoting the Popularization of Renewable Energy in Agriculture: This study powerfully demonstrates the huge potential of renewable energy in agricultural irrigation and successfully provides effective solutions to overcome its intermittency challenges. This achievement will help accelerate the promotion and application of advanced technologies such as solar water pumps in Africa, thereby significantly reducing reliance on traditional fossil energy and actively promoting the green transformation of the regional energy structure.

Supporting Sustainable Development Goals (SDGs): This intelligent co- management framework directly or indirectly contributes to the achievement of multiple United Nations Sustainable Development Goals (SDGs), including SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), highlighting its important role in the global sustainable development agenda.

Policy Formulation Reference: The results of this study clearly show that comprehensive water-energy co-management strategies are far superior to single-resource optimization in terms of improving efficiency and sustainability. Therefore, policymakers should actively encourage inter-departmental cooperation, promote the deep integration of water and energy management policies, and increase support for the research and promotion of smart agricultural technologies in Africa, with a view to achieving broader socio-economic benefits.

6.3. Research Limitations and Future Outlook

Despite the significant progress made in this study, some limitations still exist, which also point the way for future in-depth research:

Data Availability: Although this study aims to address the challenge of data scarcity in African regions by introducing transfer learning techniques, the diversity and complexity of agricultural data in this region still pose a significant challenge. Future research can further explore more advanced data fusion techniques and unsupervised learning methods to significantly improve the generalization ability and applicability of the model under different geographical and climatic conditions.

Deep Integration of Socio-Economic Factors: This study has initially considered some economic factors in the optimization model. However, the deep integration of non-technical socio-economic factors such as social equity, farmers' willingness to adopt technology, and local cultural customs still needs to be strengthened. Future research can further introduce behavioral economics and sociological theories to construct more comprehensive multi-objective functions, with a view to more accurately reflecting the actual needs and preferences of local communities, thereby enhancing the social adaptability and acceptance of the solutions.

Long-term Resilience under Climate Change Scenarios: This study primarily focuses on short-term and medium-term optimization and scheduling strategies. Future research can further combine advanced climate change prediction models to deeply evaluate the long-term resilience and adaptability of this framework under different climate change scenarios, and actively explore more robust and forward-looking adaptive management strategies to cope with the uncertainties brought by future climate change.

Technology Promotion and Scalable Application: Although this study emphasizes the application of low-cost technologies, the large-scale promotion of smart agricultural systems in Africa still faces many challenges such as weak infrastructure, insufficient capital investment, and lack of technical training. Future research should focus on business model innovation, developing effective policy incentive mechanisms, and building community participation models to promote the widespread application and sustainable development of smart agricultural technologies.

More Complex Cropping Systems: This study primarily focuses on the management optimization of a single crop. Future research can be further extended to multi-crop rotation systems, deeply exploring the competition and synergy between different crops in water and energy utilization, thereby achieving more complex and comprehensive optimization of agricultural ecosystems to meet diverse agricultural production needs.

In summary, this study provides a solid framework for smart water and energy co- management in agriculture in arid African regions. Through continuous innovation and interdisciplinary cooperation, it is expected to provide valuable experience and solutions for regions facing similar challenges worldwide, and jointly move towards a sustainable agricultural future.

7. Conclusion

This study addresses the severe challenges of water scarcity and unstable energy supply faced by agriculture in arid African regions by innovatively proposing and validating a data-driven intelligent water and energy co-management framework. This framework cleverly draws upon the core concept of "flexibility" from power systems' "smart renewable electricity portfolios," and through deep integration of smart sensor networks, advanced machine learning prediction models, and efficient multi-objective optimization algorithms, successfully achieves dynamic, synergistic, and refined scheduling of agricultural water and energy resources.

The research results clearly demonstrate that the framework proposed in this study can significantly improve water resource utilization efficiency (water saving rate exceeding 20%), substantially reduce energy costs (fossil fuel consumption reduced by over 30%), and effectively promote an increase in crop yields (yield increase exceeding 10%) in arid African regions. By precisely optimizing irrigation plans, water pump operation strategies, and the charging/discharging scheduling of energy storage systems, the system can effectively smooth the volatility of crop water demand and renewable energy supply, thereby powerfully ensuring the continuity and sustainability of agricultural production. Furthermore, rigorous case studies and field application results have further strongly confirmed the excellent effectiveness and immense application potential of this framework in actual agricultural scenarios.

This study's theoretical contribution lies in successfully introducing the concept of "flexibility" from power systems into the field of agricultural water-energy coupled management, providing a new theoretical perspective and methodology for solving the problem of resource volatility in agricultural production. Its practical significance lies in providing an operable, efficient, and environmentally friendly comprehensive solution for the sustainable development of agriculture in Africa and other arid regions worldwide. This has profound implications for enhancing regional food security, improving farmer livelihoods, and accelerating the popularization of renewable energy in agriculture. Although this study still has certain limitations in terms of data availability and the deep integration of socio-economic factors, it undoubtedly lays a solid foundation for future smart agriculture research and technology promotion.

Looking ahead, we will continue to explore more advanced data fusion technologies and unsupervised learning methods to significantly improve the generalization ability of the model under different geographical and climatic conditions. At the same time, we integrated socio-economic factors more deeply and construct more comprehensive multi-objective functions to more accurately reflect the actual needs and preferences of local communities. In addition, by combining climate change prediction models, we evaluated the long-term resilience of this framework under different climate change scenarios, and conduct in-depth research on business models and policy incentive mechanisms for technology promotion and large-scale application, in order to contribute more to the green transformation and sustainable development of African agriculture.

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AVAILABILITY OF DATA

Not applicable.

ETHICAL STATEMENT

All participants provided written informed consent prior to participation. The experimental protocol was reviewed and approved by an institutional ethics committee, and all procedures were conducted in accordance with relevant ethical guidelines and regulations.

AUTHOR CONTRIBUTIONS

Saandi Youssouf developed the conceptual framework for smart water–energy co-management, conducted the system modeling and machine learning analysis, performed the optimization simulations, and drafted the manuscript, while Hao Jiang conceived and supervised the study, contributed to the design of the renewable energy–water coupling architecture, guided the interpretation of the results, and revised the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.