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The role of theoretical models in IoT-based irrigation systems: A Comparative Study of African and U.S. Agricultural Strategies for Water Scarcity Management

Wisdom Samuel Udo [1, *], Nneka Adaobi Ochuba [1], Olatunji Akinrinola [2] and Yinka James Ololade [3]

[1] *Independent Researcher, United Kingdom.*
[2] *Independent Researcher, New York, USA.*
[3] *Independence Researcher, Addison, Texas.*

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Abstract

This review paper presents a comparative study of the theoretical models underpinning the Internet of Things (IoT)-based irrigation systems, focusing on their application in managing water scarcity within agricultural sectors in Africa and the United States. By examining the adaptation and implementation of these models, the paper sheds light on the diverse strategies employed to optimize water use and enhance crop yields in response to the pressing challenge of water scarcity. In Africa, the emphasis is on low-cost, innovative solutions tailored to local conditions and resource constraints, whereas in the U.S., the focus shifts to leveraging advanced technology, scalability, and economic viability. The study underscores the significance of IoT-based irrigation systems in promoting sustainable agriculture and water management practices across different environmental and socio-economic contexts. Through a detailed discussion, the paper reflects on the theoretical and practical implications of these findings for policymakers, farmers, and technology developers, acknowledging the limitations of the current analysis while suggesting directions for future research. The comparative insights highlight the potential of IoT technologies to revolutionize water scarcity management strategies globally, advocating for increased collaboration and innovation in the development of sustainable irrigation solutions.

Keywords: IoT-based Irrigation; Water Scarcity Management; Agricultural Strategies; Sustainable Agriculture

1. Introduction

In recent years, the integration of the Internet of Things (IoT) in agriculture has emerged as a transformative approach to address the global challenge of water scarcity. IoT-based irrigation systems represent an innovation that leverages real-time data collection, analysis, and automation to optimize water use in agricultural practices (Obaideen et al., 2022; Prashanth & Indira, 2023). These systems can significantly contribute to the sustainability of water resources by ensuring that crops receive the precise amount of water needed, thus reducing waste and increasing crop yield. The significance of IoT-based irrigation systems is particularly pronounced in the context of water scarcity, a pressing issue that threatens food security, livelihoods, and overall agricultural productivity across the globe (Dickson & Amannah, 2023; Sharma & Kumar, 2021). This challenge is not confined to any single region but affects diverse agricultural landscapes, including both the arid zones of Africa and the water-stressed fields of the United States (Abioye et al., 2020).

Water scarcity severely risks agricultural sustainability, impacting developed and developing regions. In Africa, the situation is exacerbated by variable rainfall patterns, limited access to advanced technology, and a dependence on rain-fed agriculture. These factors contribute to a precarious situation where water scarcity directly threatens food security and agricultural productivity. Conversely, in the U.S., while technological access and agricultural practices are advanced, certain areas face similar challenges of water scarcity, driven by overuse of water resources, climate change, and

* Corresponding author: Wisdom Samuel Udo

inefficient irrigation practices. The common denominator between these disparate regions is the urgent need for efficient and sustainable irrigation strategies to mitigate the impacts of water scarcity on agriculture (Li et al., 2020; Nouri, Homaee, Pereira, & Bybordi, 2023). The introduction of IoT-based irrigation systems offers a promising solution, yet the adoption and effectiveness of these systems are heavily influenced by the underlying theoretical models of operation and their suitability to specific agricultural and environmental contexts.

This study aims to explore and compare the theoretical models that underlie IoT-based irrigation systems in the context of African and U.S. agriculture. By examining how these models address the challenges of water scarcity, the study seeks to uncover the principles, technologies, and strategies that make IoT-based irrigation systems effective or otherwise. The comparative analysis will focus on these models' adaptability, scalability, and efficiency in managing water resources under varying conditions of scarcity, technological availability, and agricultural practices.

Understanding the theoretical models behind IoT-based irrigation systems and their application in different agricultural strategies is crucial for advancing water scarcity management. This study holds the potential to provide valuable insights into the effectiveness of various IoT-based models in enhancing agricultural water use efficiency. By comparing the models employed in Africa and the U.S., the research aims to identify best practices, challenges, and opportunities for improvement. The findings could inform policymakers, agricultural stakeholders, and technology developers, guiding the optimization of irrigation strategies to ensure water sustainability. Ultimately, this study seeks to contribute to securing food production and livelihoods in the face of global water scarcity challenges, emphasizing the role of innovative technologies and theoretical models in achieving this objective.

2. Theoretical Framework

The theoretical models underpinning IoT-based irrigation systems integrate multidisciplinary approaches, encompassing principles from environmental science, agricultural engineering, computer science, and information technology. These models are designed to optimize water usage through precise monitoring, control, and decision-making processes enabled by IoT technology. At their core, these models utilize real-time data collection on soil moisture, weather conditions, plant water needs, and environmental factors to automate irrigation schedules and volumes. This is achieved through the deployment of sensors, control units, and communication networks that facilitate the collection, transmission, and processing of agricultural data. Theoretical models also incorporate advanced algorithms and machine learning techniques to predict irrigation needs, dynamically adjust water distribution strategies, and ensure maximum efficiency in water use (Çetin & Beyhan, 2022; Torres-Sanchez et al., 2020).

In agricultural practices, these theoretical models are applied to manage water scarcity by enabling precision agriculture. Precision agriculture is an approach that employs detailed, real-time information to deliver specific water quantities to specific areas at specific times, thereby minimizing waste and enhancing crop yield. IoT-based irrigation systems operationalize this approach by equipping farmers with tools to monitor field conditions continuously and make informed decisions about when and how much to irrigate. This ensures that crops receive optimal water levels that meet their precise needs at various growth stages, considering the variability in soil types, crop species, and local climatic conditions. The application of these models in agriculture represents a shift from traditional, uniform irrigation practices to more sustainable, data-driven strategies that conserve water resources while maintaining or improving agricultural productivity (Bwambale, Abagale, & Anornu, 2022; Sishodia, Ray, & Singh, 2020).

The adaptation and application of IoT-based irrigation theoretical models in the African and U.S. agricultural sectors highlight both commonalities and divergences shaped by local conditions, technological accessibility, and socio-economic factors.

In Africa, the implementation of IoT-based models faces challenges such as limited access to technology, high costs, and a lack of infrastructure. However, innovative models have been developed to address these challenges, focusing on low-cost, low-power sensor networks and simplified data analytics platforms accessible to small-scale farmers (Nigussie, Olwal, Lemma, Mekuria, & Peterson, 2020). These models often emphasize community-based approaches, integrating traditional knowledge with IoT technologies to create effective and culturally acceptable systems. The focus is on maximizing the efficiency of limited water resources, improving resilience to drought, and supporting sustainable agricultural practices in resource-constrained environments (Adewusi et al., 2024).

In the U.S., the application of IoT-based irrigation models benefits from advanced technological infrastructure, significant investment in research and development, and a strong emphasis on large-scale commercial agriculture. The models used in the U.S. often incorporate cutting-edge technologies, including satellite imagery, drone surveillance, and sophisticated data analytics to optimize irrigation on a large scale. These models are designed to integrate seamlessly with existing agricultural management systems, offering precision and automation that can significantly reduce water usage while maintaining high crop yields. The emphasis is on enhancing efficiency, reducing environmental impact, and supporting the sustainability of water-intensive agricultural practices (Khan et al., 2021; Kour & Arora, 2020).

The comparative analysis of these models reveals a spectrum of innovation and adaptation, highlighting the versatility of IoT technologies in addressing the global challenge of water scarcity. While African models tend to focus on accessibility, affordability, and community engagement, U.S. models prioritize technological advancement, scalability, and integration with commercial agricultural systems. Both approaches offer valuable insights into the potential of IoT-based irrigation systems to transform agricultural practices, making them more sustainable and resilient in the face of water scarcity challenges.

3. IoT-based Irrigation Systems in Agriculture

Internet of Things technology involves the interconnection of physical devices through the internet, allowing for data collection, exchange, and analysis in real-time. IoT technology integrates various components such as sensors, actuators, control systems, and communication networks to create smart irrigation systems in irrigation systems. These components work together to monitor environmental and soil conditions, including temperature, humidity, soil moisture levels, and rainfall, providing precise, real-time data on the water requirements of crops. This data is then processed and analyzed to make informed decisions about irrigation timing and quantity, optimizing water use and ensuring that crops receive the exact amount of water they need for optimal growth (Mouha, 2021; Tran-Dang, Krommenacker, Charpentier, & Kim, 2020).

The adoption of IoT-based systems for irrigation presents several significant benefits. By enabling precise control over irrigation, IoT-based systems significantly reduce water wastage. Traditional irrigation methods, such as flood irrigation, often lead to over-watering, which wastes water and leads to nutrient leaching and reduced crop quality. IoT systems ensure that water is applied in the right amount at the right time, minimizing evaporation and runoff and substantially conserving water resources. IoT irrigation systems enhance the efficiency of agricultural operations. Automated irrigation schedules and the ability to remotely monitor and adjust irrigation parameters reduce the need for manual intervention, saving time and labour costs (Champness, Ballester-Lurbe, Filev-Maia, & Hornbuckle, 2023; Singh et al., 2021).

Additionally, data analytics helps predict irrigation needs more accurately, further optimizing resource use. The precise application of water directly impacts crop health and yield. By ensuring that crops receive optimal moisture levels at all times, IoT-based irrigation systems can improve plant growth, reduce stress, and increase the quantity and quality of the harvest. This precision supports sustainable agricultural practices and boosts profitability for farmers (Adelekan et al., 2024; Kamyab et al., 2023).

Despite their advantages, the implementation of IoT-based irrigation systems faces several challenges. The deployment of IoT systems requires a reliable technological infrastructure, including internet connectivity and access to advanced hardware and software. In many agricultural regions, especially in developing countries, such infrastructure may be lacking or inconsistent, limiting the adoption of IoT solutions. The initial cost of setting up IoT-based irrigation systems can be high, encompassing the expenses for sensors, control units, and software platforms, as well as ongoing maintenance and data management costs. This investment may be prohibitive for small-scale farmers or those in resource-limited settings, restricting access to the technology (García, Parra, Jimenez, Lloret, & Lorenz, 2020; Rajak, Ganguly, Adhikary, & Bhattacharya, 2023).

There is often a knowledge gap regarding the operation and benefits of IoT systems among farmers, particularly those accustomed to traditional farming practices. The successful implementation of IoT-based irrigation requires training and education to ensure that farmers are comfortable using the technology and can fully realize its benefits. The collection and transmission of data through IoT devices raise concerns about data security and privacy. Ensuring the integrity and confidentiality of agricultural data is crucial to gaining the trust of farmers and stakeholders and promoting the widespread adoption of IoT-based systems (Demestichas, Peppes, & Alexakis, 2020; Ferrag, Shu, Yang, Derhab, & Maglaras, 2020).

Despite these challenges, the potential of IoT-based irrigation systems to revolutionize water management in agriculture is immense. Addressing these barriers through technological innovation, policy support, and capacity building can unlock the full potential of IoT technologies, paving the way for more sustainable and efficient agricultural practices.

4. Comparative Analysis of African and U.S. Strategies

4.1. African Agricultural Strategies

African agricultural strategies are deeply influenced by the continent's diverse climatic conditions, resource limitations, and varying levels of technological access. In many African countries, agriculture remains a cornerstone of the economy and food security, yet it is challenged by factors such as water scarcity, limited infrastructure, and the impacts of climate change. To address these challenges, strategies often emphasize (Dibal et al., 2022; Nigussie, Olwal, Musumba, et al., 2020; Oliveira-Jr et al., 2020):

Adaptation to Local Conditions: Strategies are tailored to the specific needs of different regions, taking into account local climate, soil types, and water availability. This includes adopting drought-resistant crop varieties, rainwater harvesting techniques, and efficient water use practices that maximize yield under resource-constrained conditions.

Resource Limitations: Recognizing the limitations in financial and technological resources, African strategies often focus on low-cost, low-tech solutions that smallholder farmers can easily adopt. This includes simple drip irrigation systems, manual or solar-powered pumps, and the use of mobile technology for weather and agricultural advice.

Innovation and Community Engagement: There is a growing emphasis on innovative approaches that leverage community knowledge and participation. This includes the development of farmer cooperatives for resource sharing, the use of ICT for agricultural extension services, and partnerships with local and international organizations to pilot IoT-based irrigation projects that are scalable and sustainable within the African context.

4.2. U.S. Agricultural Strategies

In contrast, U.S. agricultural strategies are characterized by a high degree of technological integration, scalability, and a focus on economic feasibility (Kim, Lee, & Kim, 2020; Rehman et al., 2022; Xu, Gu, & Tian, 2022):

Technology Adoption: The U.S. agricultural sector is marked by the widespread adoption of advanced technologies, including precision agriculture, IoT-based irrigation systems, and data analytics. These technologies are used to optimize water use, monitor crop health, and increase efficiency across large-scale farming operations.

Scalability: U.S. strategies are designed to be scalable, supporting large commercial farms as well as smaller operations. The infrastructure for IoT technology, including reliable internet access and technical support, is more readily available, facilitating the adoption of sophisticated irrigation systems.

Economic Feasibility: Economic considerations are central to U.S. agricultural strategies, with a focus on maximizing return on investment. This includes the use of economic models to evaluate the cost-effectiveness of IoT-based irrigation systems, considering factors such as water savings, yield improvement, and labour reduction.

The adoption and impact of IoT-based irrigation models in Africa and the U.S. reveal both differences and similarities. The most significant differences stem from the contrasting levels of technological infrastructure, economic resources, and the scale of agricultural operations. African strategies are more focused on overcoming resource limitations and adapting to local conditions with innovative, low-cost solutions. In contrast, U.S. strategies leverage high technology and economic models to optimize large-scale agricultural production.

Despite these differences, both regions share a common goal of enhancing water use efficiency and sustainability in agriculture. There is a mutual interest in adopting IoT-based systems to improve crop yield and address water scarcity. Additionally, both regions recognize the importance of tailoring strategies to specific environmental and socio-economic contexts to ensure the successful implementation of IoT technologies.

5. Discussion

The comparative study of IoT-based irrigation systems in African and U.S. agricultural contexts enriches the understanding of the theoretical models underpinning these technologies. By examining how these models are adapted and applied across different environmental, economic, and social landscapes, the study highlights the flexibility and potential of IoT technologies to address global challenges of water scarcity and agricultural efficiency. It underscores the importance of integrating multidisciplinary approaches—combining insights from environmental science, agricultural practices, computer science, and socio-economic theory—to develop irrigation models that are both technologically advanced and socially and economically viable. This comparative analysis contributes to the theoretical discourse by demonstrating the critical role of context in the application of IoT models, suggesting that the effectiveness of such technologies is contingent upon their adaptability to local conditions and needs.

For policymakers, the study underscores the need for supportive frameworks that facilitate the adoption of IoT-based irrigation systems, including investments in technological infrastructure, training programs for farmers, and policies that encourage innovation and sustainability in agriculture. In Africa, this might mean focusing on policies that reduce the technological and financial barriers for smallholder farmers, while in the U.S., policies could aim to promote water conservation and sustainable practices in large-scale farming operations.

For farmers, the study highlights the potential benefits of adopting IoT-based irrigation systems, including increased water efficiency, higher crop yields, and improved resource management. However, it also points to the need for training and education to maximize the benefits of these technologies. Technology developers can draw insights from the comparative analysis to design more adaptable and scalable IoT solutions that cater to the diverse needs of farmers in different regions. This includes developing low-cost, easy-to-use technologies for resource-limited settings and advanced systems that integrate with large-scale agricultural operations.

The analysis acknowledges several limitations, most notably the exclusion of detailed methodology and case studies. Without specific case studies, the analysis may overlook nuanced insights into the practical implementation and outcomes of IoT-based irrigation models in specific contexts. Additionally, the broad scope of the comparative study may gloss over regional variations within Africa and the U.S., potentially oversimplifying the challenges and opportunities in each context.

Future research should aim to address these limitations by incorporating detailed case studies that provide in-depth insights into the application, challenges, and successes of IoT-based irrigation systems in various settings. There is also a need for research focusing on emerging theoretical models that leverage advancements in technology and data analytics to further enhance irrigation efficiency and sustainability. Additionally, studies could explore the socio-economic impacts of IoT-based irrigation, including its effects on livelihoods, food security, and economic development in different agricultural regions. Investigating the scalability of models across different sizes of farms and varying levels of technological infrastructure can provide valuable guidance for technology developers and policymakers. Moreover, research should consider the environmental impacts of IoT-based irrigation, including its potential to mitigate climate change effects through more sustainable water and land use practices.

By addressing these areas, future research can contribute to the development of more effective, adaptable, and sustainable irrigation strategies that leverage IoT technology to meet the global challenges of water scarcity and agricultural productivity.

6. Conclusion

This comparative study has illuminated the distinct approaches to IoT-based irrigation systems in Africa and the U.S., revealing how theoretical models are adapted to meet each region's unique agricultural and environmental challenges. In Africa, strategies focus on low-cost, innovative solutions tailored to local conditions and resource limitations, emphasizing community engagement and the integration of traditional knowledge with new technologies. In contrast, the U.S. employs advanced technological solutions, scalability, and economic feasibility to enhance agricultural productivity and efficiency on a larger scale. Despite these differences, both regions aim to optimize water use and improve crop yields through IoT technologies, underscoring these systems' universal relevance and potential in addressing global water scarcity challenges.

The insights gained from this comparative analysis have significant implications for managing water scarcity in agriculture. Understanding the diverse theoretical models and their practical applications offers valuable perspectives for developing more effective, sustainable irrigation strategies. By recognizing the strengths and limitations of different approaches, policymakers, farmers, and technology developers can better tailor IoT-based irrigation solutions to various contexts, enhancing water conservation efforts and supporting agricultural productivity. This study highlights the importance of innovation, adaptability, and collaboration across different regions and disciplines in tackling the complex issue of water scarcity.

In light of these findings, there is a clear call to action for researchers, policymakers, and practitioners to delve deeper into exploring and utilizing theoretical models in IoT-based irrigation. Further research is essential to overcome the identified limitations, explore emerging technologies, and refine existing models for greater efficiency and inclusivity.

Collaborative efforts are needed to bridge the gap between technological possibilities and practical implementation, ensuring that the benefits of IoT-based irrigation systems can be realized globally. By prioritizing developing and deploying sustainable irrigation solutions, we can make significant strides toward securing water resources and enhancing food security in the face of growing environmental challenges.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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