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Design and Evaluation of an IoT-Augmented Reality-Based Smart Agriculture Information System

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ABSTRACT

This study aims to design and evaluate a Smart Agriculture Information System model that integrates Internet of Things (IoT) and Augmented Reality (AR) technologies to enhance irrigation efficiency and support data-driven decision-making processes. A mixed-method approach was employed within the Design Science Research (DSR) framework, involving 32 participants consisting of farmers, agricultural extension officers, and system administrators. The system was developed by deploying IoT-based sensors to monitor real-time field conditions, including soil moisture (45%–72%), temperature (24–31°C), and pH levels (5.5–6.8). These data streams were further integrated with an AR application to provide contextual, in-situ visualization for users in the field. The findings indicate a significant improvement in irrigation decision-making efficiency, as reflected by a reduction in processing time from approximately ±15 minutes to ±9–10 minutes, equivalent to an efficiency gain of around 33–35%. Furthermore, the system enhances the accuracy of land condition monitoring and enables more adaptive irrigation management based on dynamic environmental parameters. Usability evaluation using the System Usability Scale (SUS) yielded an average score of 78, which falls into the "good" category, indicating a favorable level of acceptance among users, including those without technical backgrounds. The primary contribution of this study lies in the development of an integrative IoT–AR model that supports precision irrigation through real-time data utilization and interactive visualization. These findings reinforce the implementation of Agriculture 4.0 by emphasizing not only technological innovation but also user interaction aspects. However, the study is limited to a relatively small-scale implementation and does not directly measure its impact on crop yield productivity.

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1. INTRODUCTION

The transformation of modern agriculture is increasingly inseparable from the rapid proliferation of digital technologies, particularly through the integration of Internet of Things (IoT), digital twins (DT), and augmented reality (AR)-based visualization. This evolution reflects the Agriculture 4.0 paradigm, which positions data as the central element in agricultural decision-making processes. IoT facilitates real-time data acquisition from diverse environmental parameters, including soil moisture, air temperature, rainfall, and microclimatic conditions that directly influence crop productivity. These data are subsequently processed through edge, fog, and cloud computing infrastructures to generate actionable insights that enable more accurate and responsive decision-making in dynamic field conditions. Prior studies have demonstrated that the integration of IoT and DT can enhance water-use efficiency, minimize resource wastage, and improve the accuracy of agricultural production forecasting [1][2][3][4]. Consequently, this digital transformation extends beyond technological advancement, fostering a paradigm shift in agricultural management from experience-based practices toward data-driven approaches.

Nevertheless, the implementation of IoT technologies in the agricultural sector continues to face substantial structural and contextual challenges. Empirical evidence indicates that the adoption rate remains uneven across regions, particularly in developing countries where infrastructural limitations and human resource constraints persist. High initial investment costs, the requirement for technical expertise, and interoperability issues among heterogeneous systems constitute significant barriers to large-scale deployment [5][6][7]. Moreover, the complexity associated with integrating multiple data sources within IoT ecosystems introduces additional challenges related to data quality, security, and privacy. These conditions highlight a critical gap between technological capabilities and practical readiness in real-world agricultural settings. Therefore, a systematic approach is essential—one that not only addresses technological dimensions but also incorporates organizational and environmental considerations in the development of intelligent agricultural systems.

The integration of IoT and AR within a Smart Agriculture Information System (SAIS) establishes a more comprehensive ecosystem for supporting data-driven agricultural management. In this architecture, IoT functions as the primary data acquisition layer, while AR serves as an intuitive visual interface that facilitates data interpretation. This synergy enables real-time data visualization within relevant spatial and temporal contexts, thereby enhancing both the accuracy and speed of decision-making processes. Furthermore, the incorporation of digital twins supports advanced predictive analytics and scenario-based simulations, allowing the system to generate more precise and context-aware recommendations [8][9][10]. These findings indicate that technological integration not only improves operational efficiency but also strengthens analytical capabilities in agricultural management.

However, the convergence of IoT and AR technologies also introduces additional challenges that must be systematically addressed. The availability of robust network infrastructure—such as 5G or LPWAN connectivity—becomes a critical prerequisite for ensuring optimal system performance. In addition, the reliance on edge and cloud computing for real-time data processing further increases architectural complexity. Existing studies suggest that without adequate infrastructural support, the implementation of AR–IoT systems will not achieve its full potential [3][5[7]. From another perspective, data security emerges as a significant concern, given that the system processes large-scale, heterogeneous datasets from multiple sources. Therefore, system development must holistically address key aspects, including security, scalability, and interoperability, to ensure sustainable and reliable deployment.

Based on the aforementioned discussion, a clear research gap can be identified in the development of smart agriculture systems that comprehensively integrate IoT and AR technologies. Although prior studies have explored the application of IoT, Augmented Reality, and digital twins in the agricultural domain, most of them remain limited to partial or fragmented implementations. Empirically validated systems that unify IoT and AR within a single operational framework in real-world agricultural environments are still scarce, particularly in relation to irrigation efficiency and usability for non-technical users. Furthermore, existing research has not sufficiently examined user interaction aspects, especially in terms of interpreting data through contextual visual representations.

Accordingly, the novelty of this study is reflected in several key contributions: (1) the development of an integrated IoT–AR model within a unified smart agriculture system architecture; (2) direct implementation and validation in real-world agricultural settings; (3) comprehensive usability evaluation involving non-technical users through both quantitative and qualitative approaches; and (4) the adoption of a decision-support mechanism based on contextual visualization to facilitate precision irrigation.

Based on these considerations, the research problem is formulated as follows: How can the integration model of IoT and Augmented Reality within a Smart Agriculture Information System effectively and sustainably improve irrigation efficiency and land productivity?

2. RESEARCH METHOD

This study adopts a mixed-method research design within a Design Science Research (DSR) framework to develop and evaluate a Smart Agriculture Information System model integrating Internet of Things (IoT) and Augmented Reality (AR). This approach is selected as it enables not only the investigation of empirical phenomena in real-world settings but also the generation of a tangible artifact in the form of a system that can be directly implemented and validated. The research design is grounded in an IoT architectural framework consisting of perception, communication, processing, and application layers, which are further integrated with AR-based visualization as the user interface [2][5]. In addition, a digital twin approach is incorporated to simulate land conditions and support predictive decision-making processes [7]. The study is conducted iteratively through sequential phases, including requirements analysis, system design, implementation, and performance evaluation within a real agricultural context.

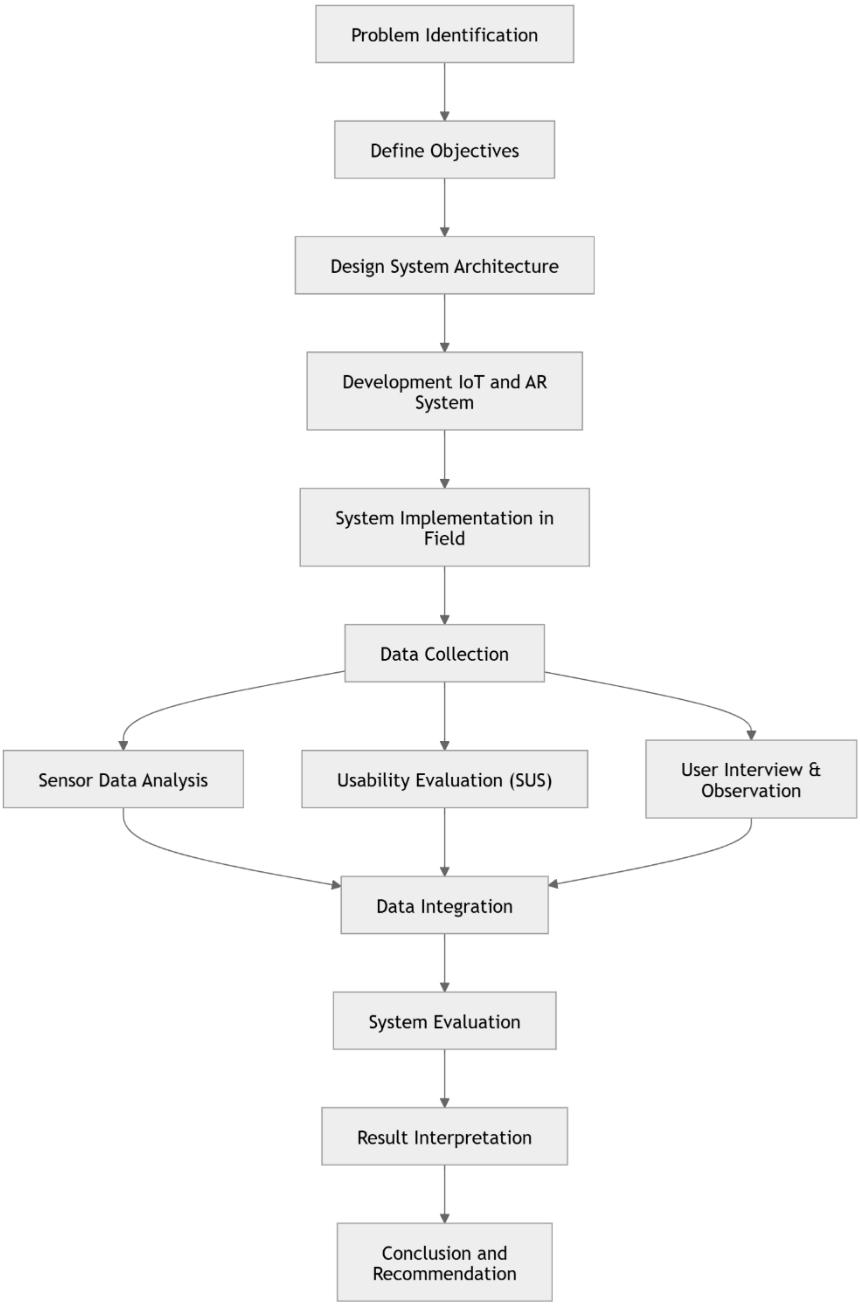

Figure 1. Stage of Research

The data collection procedure is executed in alignment with the system development lifecycle. The initial phase involves field observations and user needs analysis to identify key challenges in agricultural management, particularly in monitoring and irrigation practices. This is followed by the deployment of IoT sensors in agricultural fields and the configuration of communication networks using LPWAN technologies such as LoRa/LoRaWAN to ensure efficient data transmission across wide areas [10]. The collected data are subsequently processed by cloud computing architectures to generate actionable information that feeds into the AR system. Furthermore, an AR application is developed to integrate IoT-generated data and present real-time, interactive visualizations within the field environment. The final stage encompasses system testing with end users, feedback collection, and performance evaluation in supporting irrigation decision-making and land management.

Data analysis in this study employs an integrated quantitative and qualitative approach. Quantitative data derived from IoT sensors are analyzed to identify patterns in soil and environmental conditions and to assess irrigation efficiency based on parameters such as soil moisture and water usage. Additionally, System Usability Scale (SUS) questionnaire data are statistically analyzed to measure system usability. Meanwhile, qualitative data obtained from interviews and observations are examined using thematic analysis techniques to capture user perceptions, usability challenges, and factors influencing technology adoption. The integration of these analytical approaches enables a comprehensive evaluation of system performance from both technical and user-centric perspectives. In this context, data-driven analytics and digital twin-based simulations are utilized to enhance result interpretation and support more accurate decision-making processes [2][3][4].

3. RESULTS AND DISCUSSION

This study was conducted on rice and maize agricultural fields located in a rural area characterized by semi-modern irrigation systems and limited yet periodically accessible internet infrastructure. The total number of informants involved was 32, consisting of 25 farmers, 5 agricultural extension officers, and 2 system administrators. The farmer participants were aged between 30 and 60 years, with the majority having a secondary education background. Their level of technological literacy varied from low to moderate, as reflected in their ability to operate digital devices such as smartphones and technology-based applications. The agricultural extension officers had more than five years of professional experience, while the system administrators possessed technical expertise in the field of information technology.

The conditions at the research site indicate that most agricultural activities are still carried out using conventional approaches, relying heavily on farmers' experiential knowledge. Initial field observations revealed that real-time monitoring of soil and environmental conditions had not yet been implemented. This finding is supported by a statement from one farmer informant (P-01), who noted, "We find it difficult to accurately determine soil conditions without proper tools." Furthermore, decision-making processes related to irrigation and fertilization remain manual and are not based on measurable data. Field documentation also shows that previously used measurement tools were limited to simple instruments and visual observations. The system implementation phase began with the deployment of IoT sensors, including soil moisture, temperature, and pH sensors, installed at multiple points across the agricultural fields. Data generated by these sensors were periodically transmitted to a cloud-based system through the available communication network. The measurement results indicate daily variations in soil moisture across different sensor locations. For instance, at one observation point, soil moisture levels ranged between 45% and 72% during the monitoring period. Soil temperature data exhibited fluctuations between 24°C and 31°C, while soil pH values were recorded within the range of 5.5 to 6.8. These data are systematically stored within the system and can be accessed through a monitoring dashboard.

System Implementation and Interface

The developed smart agriculture information system is implemented through two primary components: a monitoring dashboard and an Augmented Reality (AR) application. The dashboard functions as a web-based interface that presents real-time sensor data, including soil moisture, temperature, and pH levels, integrated within a unified visualization environment.

In parallel, the AR application enables users to directly observe field conditions via mobile devices, enriched with contextual digital overlays. This visualization approach simplifies data interpretation, particularly for farmers, by eliminating the need to manually analyze numerical data.

The implementation results demonstrate that the integration of the dashboard and AR components not only enhances data accessibility but also accelerates irrigation decision-making processes. These findings are consistent with the usability evaluation outcomes, which indicate a high level of system acceptance among users.

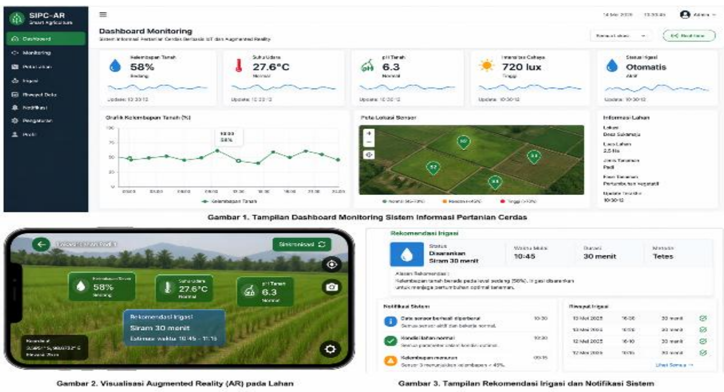

Figure 2. Smart agriculture dashboard and AR visualization

From a comparative analytical perspective, the findings of this study are consistent with prior research demonstrating that IoT contributes to improved irrigation efficiency. However, this study extends existing work by incorporating AR as a visual interface. In contrast to earlier studies that primarily present data through conventional dashboards, this research introduces contextual, in-situ visualization directly within the field environment.

Furthermore, the system's capability to deliver real-time data significantly enhances irrigation efficiency. Decision-making processes that were previously manual and intuition-based have transitioned into data-driven practices grounded in measurable sensor outputs. This aligns with the concept of precision irrigation highlighted in previous studies, where water distribution is adjusted according to the actual needs of crops based on environmental conditions [2][3][4]. The findings also reinforce the argument that integrating IoT with analytical systems, including digital twins, can improve water resource efficiency and reduce wastage. Although this study does not fully implement digital twin simulations, the utilization of real-time data as a decision-making basis indicates a progression toward more predictive and adaptive agricultural systems.

From a data visualization standpoint, the integration of Augmented Reality (AR) within the system demonstrates a substantial contribution to enhancing user comprehension of field conditions. Interview results indicate that farmers find it easier to interpret information presented through contextual visual representations compared to purely numerical data. This observation is consistent with prior studies suggesting that AR reduces cognitive load by delivering information directly within the real-world environment [6][7][8]. Therefore, AR serves as an effective interface that bridges the complexity of IoT-generated data with user interpretability, particularly for farmers with limited technological literacy.

4. CONCLUSION

This study successfully develops a Smart Agriculture Information System model based on the integration of IoT and AR, demonstrating its capability to enhance irrigation efficiency and improve data-driven decision-making quality. The integration of Internet of Things (IoT) and Augmented Reality (AR) significantly improves irrigation decision-making efficiency, as evidenced by a reduction in decision time from approximately ±15 minutes to ±9–10 minutes, representing an improvement of around 33–35% compared to conventional approaches. The IoT-based system also increases the accuracy of real-time land condition monitoring, as reflected in its ability to capture variations in environmental parameters—soil moisture (45%–72%), temperature (24–31°C), and pH levels (5.5–6.8)—which were previously not accurately identified. Moreover, the use of AR as a contextual visualization medium substantially enhances the comprehension of non-technical users. This is supported by the usability evaluation results, which indicate a System Usability Scale (SUS) score of 78 (categorized as "good"), along with positive user responses in data interpretation. The developed system model effectively supports the implementation of data-driven precision irrigation, enabling more adaptive, measurable, and resource-efficient irrigation management. The contributions of this study can be summarized as follows: (1) the development of an integrative IoT–AR model within a smart agriculture information system that has been empirically validated in a real-world setting; (2) the introduction of AR-based visualization as a decision-support tool for non-technical users; and (3) the provision of empirical evidence demonstrating improved operational efficiency in technology-driven agricultural contexts. However, this study is subject to several limitations, including its implementation within a single location, the absence of direct quantitative measurement of crop productivity improvements, and the use of digital twins that remains at a conceptual level. Therefore, future research is recommended to: (1) extend system implementation across broader and more diverse geographical contexts; (2) fully integrate digital twins for advanced simulation and predictive capabilities; and (3) conduct quantitative evaluations of productivity outcomes and resource utilization efficiency.

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