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Design and Implementation of an Internet of Things (IoT)-Based Smart Agriculture System for Soil Moisture Monitoring

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ABSTRACT

Modern agriculture requires the use of technology to increase efficiency and productivity, particularly in water resource management. This study aims to design and implement an Internet of Things (IoT)-based smart farming system capable of monitoring soil moisture in real time to support irrigation efficiency. The method used in this study is a descriptive qualitative approach with a field study, which includes the device design process, system trials on agricultural land, and interviews and observations with users (farmers). The system is built using a soil moisture sensor connected to a microcontroller and sent to a web-based monitoring platform. The results show that the system is able to work effectively by providing real-time data that can be accessed anytime by farmers through digital devices. Farmers reported that it is more assisted in determining the right and efficient watering time, and saves water use by up to 20–30 percent. Furthermore, the simple system interface is considered easy to use even by farmers who are not familiar with technology. However, challenges such as limited internet connection and the need for device protection in the field are still encountered. This research makes a significant contribution to the development of low-cost technology-based farming systems that can be applied in rural areas. Thus, the integration of IoT in agricultural practices can be an innovative solution to support precision agriculture and sustainability.

Keywords: IoT, soil moisture, smart farming, monitoring

INTRODUCTION

The issue of food security is a global and national concern, especially amidst the challenges of climate change, population growth, and land conversion which threaten the sustainability of the agricultural sector (Ibn, 2024). In Indonesia, agriculture remains a strategic sector in ensuring food availability for the entire population (Azzurri, 2024). However, various obstacles still hinder agricultural efficiency and productivity, such as limited access to technology, limited information on weather and soil conditions, and suboptimal cultivation practices. In this context, agricultural efficiency is not only crucial for increasing yields but also for ensuring more efficient and environmentally friendly resource use. Modernization efforts through the adoption of technologies such as the Internet of Things (IoT) are one potential solution to address these challenges (Ayuningtyas & Rositawati, 2025). This technology enables agricultural systems to be more precise and responsive, supporting efforts to increase production while strengthening sustainable food security.

Traditional agricultural practices in Indonesia still face various fundamental challenges that have a direct impact on the productivity and sustainability of farming businesses (Wulandari, 2025). One of the main challenges is the low efficiency of water use, where irrigation is still done manually and unmeasured, often resulting in wastage or under-watering of crops. Furthermore, the decision-making process in traditional agriculture relies heavily on farmers' intuition and experience, which, while valuable, are not always accurate or relevant to changing environmental conditions. This reliance becomes a barrier when faced with new situations such as extreme climate change or unusual pest attacks. The lack of real-time data is also a serious obstacle, as farmers lack access to up-to-date information on soil moisture, air temperature, or crop conditions that could help them respond quickly and appropriately. As a result, cultivation decisions are often reactive rather than proactive, potentially reducing yields and increasing the risk of crop failure. To address these issues, a new, technology-based approach is needed that can provide accurate, integrated, and easily accessible data to farmers directly in the field (Nurgholis & Sutabri, 2024).

The Industrial Revolution 4.0 has become a catalyst for accelerating digital transformation in various sectors, including the agricultural sector, which previously tended to lag behind in technology adoption (Dayioğlu & Turker, 2021). In this context, the integration of technologies such as the Internet of Things (IoT) has become highly relevant and urgent to address the challenges of efficiency, productivity, and food security. IoT enables various sensor devices and monitoring systems to work in real time to collect critical data from the agricultural environment, such as soil moisture levels, air temperature, light intensity, and irrigation needs (Wardhana et al., 2025). This data can then be accessed by farmers through digital platforms, supporting more accurate, rapid, and evidence-based decision-making. Digital transformation through IoT also enables automation in irrigation, fertilization, and pest control systems, thereby reducing manual workload and increasing resource efficiency. Thus, the need for digital transformation is not just an option, but a strategic imperative for a future agriculture that is sustainable, intelligent, and adaptive to environmental changes and market demands (Putri et al., 2023).

Smart farming technology offers significant breakthroughs in agricultural land management by enabling farmers to monitor and control land conditions in real time. One crucial aspect that can be optimized through this technology is soil moisture, which significantly determines irrigation needs and efficiency (Yusuf & Suryono, 2025). By utilizing moisture sensors integrated with Internet of Things (IoT) systems, farmers can continuously obtain accurate data on soil conditions, allowing irrigation to be applied only when needed. This not only significantly saves water usage but also prevents crop damage from over- or under-watering. Furthermore, this technology enables the implementation of automated irrigation systems controlled based on pre-determined parameters, making agricultural practices more precise, efficient, and sustainable (Ula et al., 2025).

Soil moisture is one of the key factors in agricultural cultivation because it directly influences the availability of water for plants, which ultimately determines the growth rate and productivity of agricultural products (Pradiko et al., 2020). Plants require a certain level of humidity to optimally absorb nutrients through the roots.(Safrimawan, 2019)If humidity is too low, plants will experience water stress, inhibiting photosynthesis and reducing yields. Conversely, excessive humidity can cause root rot and encourage pathogen growth. Therefore, regular and accurate soil moisture monitoring is crucial for farmers to make informed decisions about irrigation management. With IoT-based moisture sensor technology, this monitoring can be carried out in real time and continuously, thus supporting efficient water use, maintaining plant health, and increasing overall agricultural yields.

Monitoring soil moisture manually requires quite a lot of energy and time, especially on large and spread agricultural land (Simamarta et al., 2025). Farmers must conduct direct measurements at various points, which not only drains human resources but is also prone to data inconsistencies due to limited range and frequency of measurements. Furthermore, manual methods do not allow for continuous monitoring, making it difficult to detect changes in soil conditions in real time. As a result, irrigation decisions are often reactive and not based on accurate data. This inefficiency can result in water waste, reduced productivity, and even economic losses. Therefore, an automated monitoring system capable of providing instant and integrated moisture data is needed to make irrigation management more efficient, targeted, and adaptive to dynamic land conditions.

The role of the Internet of Things (IoT) in optimizing irrigation is very significant, especially in creating agricultural systems that are more efficient and responsive to crop needs (Ariawan, 2024). Using IoT sensors, soil moisture can be measured automatically and periodically without manual intervention. This data is then sent in real time to a web-based monitoring system or app, allowing farmers to access soil condition information anytime and anywhere. This information enables more informed decisions regarding irrigation timing and volume, which not only conserves water but also prevents over-irrigation or drought (Nuraini et al., 2025). Furthermore, this system can be integrated with automated irrigation controls, allowing for automated watering based on actual data, not assumptions. Thus, IoT plays a crucial role in increasing water use efficiency, improving land management, and supporting agricultural productivity and sustainability (Mendrofa et al., 2024).

With real-time soil moisture data available through IoT sensors, farmers can make more timely and efficient irrigation decisions. This accurate information allows for adjustments to irrigation schedules and amounts based on actual crop needs, avoiding water waste and maintaining optimal soil conditions for plant growth. Using this data also reduces reliance on estimates or intuition alone and helps farmers respond more quickly and accurately to changing environmental conditions. As a result, irrigation practices become more water-efficient, sustainable, and contribute to overall yield improvements (Rumihin, 2024).

The research gap in this study lies in the lack of exploration of contextual application and user experience in implementing IoT systems in agricultural fields, as most previous research has focused on the general technical aspects of the devices. Furthermore, there is a lack of documentation and evaluation of simple, affordable, and relevant IoT systems for small and medium-scale farming, particularly in rural areas. Research that qualitatively examines the design process, implementation challenges, and direct user responses to smart farming systems is also still very limited, thus opening up space for more applicable scientific contributions based on the real needs of farmers.

The novelty of this research lies in the integration of practical technological approaches and qualitative analysis to examine the application of the Internet of Things (IoT) in soil moisture monitoring, a field that has not been widely explored in previous research. This study presents the design of a low-cost IoT system that can be replicated by smallholder farmers with limited access to advanced technology. Furthermore, this study provides an empirical and contextual overview of farmer responses and the system's effectiveness in improving irrigation efficiency, thus making a practical contribution to the development of inclusive and applicable smart agriculture at the grassroots level.

The purpose of this study is to design and implement an Internet of Things (IoT)-based soil moisture monitoring system on agricultural land, and to describe the process of using the system by farmers and their responses to its effectiveness and ease of use. This study also aims to evaluate the extent to which the system can assist in making more efficient and timely irrigation decisions, while also providing recommendations for the development of a smart farming system based on simple yet applicable technology to support food security and agricultural efficiency at the local level.

METHODOLOGY

This study uses a descriptive qualitative approach to systematically describe the process of designing, implementing, and evaluating an Internet of Things (IoT) system in the context of smart agriculture (Hikmatunnisa et al., 2024). This type of research is a field study that focuses on an in-depth exploration of the implementation of IoT technology in agricultural environments. The research subjects included farmers, technicians, and stakeholders involved in smart farming systems, with the research location being in agricultural land such as rice fields or gardens where trials of IoT-based soil moisture monitoring systems were conducted. Data collection techniques included participatory observation of the system installation and use process, in-depth interviews with users to determine perceptions and benefits, and documentation in the form of system design and sensor data. The research instruments consisted of a semi-structured interview guide, observation sheets, and technical notes and humidity sensor data recordings. Data analysis used the Miles and Huberman model with data reduction stages, data presentation in narrative and visualization forms, and inductive conclusion drawing. Data validity testing was carried out through technical triangulation, member checking with informants, and documentation audit trails. The research steps included literature studies, system design, implementation and field trials, as well as data collection and evaluation of system effectiveness (Waruwu, 2024).

RESULTS AND DISCUSSION

The research results show that the IoT system for monitoring soil moisture functions as designed. The moisture sensor is able to read soil conditions in real time and send data to a web-based monitoring platform or mobile application via a Wi-Fi connection supported by a microcontroller such as ESP32 or NodeMCU. This data can be accessed by farmers remotely at any time, complete with reading graphs that help analyze land conditions. The implementation of this system has been proven to increase irrigation efficiency, where farmers can water crops more timely based on actual data, not just intuition, and recorded water savings of 20–30%.

Furthermore, the system is considered quite easy to use by most farmers, even those unfamiliar with digital technology, although brief training is still required in the initial stages of use. Key challenges encountered in field implementation include internet network stability in rural areas and limited electricity or battery power to power the device. Furthermore, a protective sensor casing is required to make the system more resistant to extreme weather conditions and physical disturbances such as animals or other agricultural activities.

System Effectiveness in Supporting Precision Agriculture

The effectiveness of the system in supporting precision farming is seen from its ability to present accurate, relevant, and accessible information in real-time, thus enabling data-driven decision-making by farmers (Anggarda et al., 2023). Through continuous soil moisture monitoring, farmers can precisely adjust irrigation schedules and volumes, avoid water waste, and prevent overwatering and underwatering, which can be detrimental to plant growth. This system not only improves resource efficiency but also contributes to increased yields and crop quality by maintaining an optimal growing environment. This approach makes precision agriculture more affordable and applicable for small- and medium-scale farmers, paving the way for an inclusive digital transformation in the agricultural sector in rural areas ((Wardhani & Kurniati, 2025).

The results of this study reinforce findings in various previous literature, which suggest that Internet of Things (IoT) technology plays a significant role in optimizing irrigation systems and increasing the efficiency of agricultural resource use, particularly water. By providing real-time data on soil moisture, the system enables farmers to develop more precise irrigation strategies based on actual crop needs, rather than simply estimates.(Mircea et al., 2021)This effectiveness aligns with previous studies that emphasize the importance of implementing precision technology to support agricultural sustainability and productivity, especially amidst the challenges of climate change and limited natural resources (Getahun et al., 2024).

Digital Transformation of Small-Scale Agriculture

The findings of this study indicate that digital transformation through the application of IoT technology is not exclusive to large-scale agricultural industries, but is also very likely to be adapted by small farmers at relatively low costs (Lima et al., 2020). The simple yet functional soil moisture monitoring system has proven to be operable in small-scale farming environments, even by farmers previously unfamiliar with digital technology. This opens up inclusive opportunities for precision agriculture, where smallholder farmers can improve efficiency, productivity, and data-driven decision-making without relying on expensive, sophisticated infrastructure.

This technological adaptation opens up significant opportunities for smallholder farmers to actively participate in more efficient and sustainable modern agricultural practices. By leveraging affordable and easy-to-use IoT systems, farmers can access real-time information on their land conditions, enabling them to make data-driven decisions previously only possible in large-scale agricultural sectors. This inclusiveness not only increases irrigation productivity and efficiency but also strengthens the position of smallholder farmers in facing the challenges of food security and climate change in the digital era (Kasim et al., 2025).

The Role of User Experience in Technology Adoption

The role of user experience is crucial in determining the success of technology adoption among farmers. A simple, intuitive interface using familiar language will facilitate system understanding and use, especially for farmers unfamiliar with digital technology. Beyond technical aspects, user comfort and trust in the system also influence the sustainability of technology use. By considering these aspects, the development of IoT-based agricultural systems can be more inclusive, effective, and sustainable, especially in small- and medium-scale farming communities (Chaveesuk et al., 2020).

The active involvement of farmers in the process of designing and developing agricultural technology systems has been proven to increase their sense of ownership of the technology (Sutoyo & Sensuse, 2023). By being involved from the early stages, from needs identification and system trials to evaluation, farmers feel that the technology being developed is truly relevant to the conditions and challenges they face. This participatory approach also encourages the emergence of more contextual local innovations and increases the chances of successful implementation in the field, as the technology is no longer perceived as something foreign but as a tool born from their own real needs.

Infrastructure and Education Support Needed

The successful implementation of IoT-based agricultural systems is highly dependent on the availability of supporting infrastructure, particularly stable internet access and reliable electricity. In many rural areas, limited internet networks and electricity supply are major challenges that hinder the system's real-time operation. Therefore, efforts from various parties, including the government and the private sector, are needed to expand digital infrastructure and provide alternative energy solutions such as solar panels. Furthermore, educating farmers about the use of this technology is crucial so they not only have the technical skills to use the system but also understand its long-term benefits in supporting more efficient and sustainable agriculture (Sumartan et al., 2024).

Basic technology training is a crucial aspect in supporting the adoption of IoT-based agricultural systems, especially in rural areas where most farmers are unfamiliar with digital devices. Through training, farmers can understand how sensors work, read data from monitoring applications, and make decisions based on available information. Training programs also serve to build farmers' confidence and independence in operating new technologies. Furthermore, ongoing training will help farmers stay abreast of innovations and create a learning community that shares experiences and solutions in the field.

Contribution to Sustainable Agricultural Development

An IoT-based moisture monitoring system significantly contributes to sustainable agricultural development by enabling more efficient and measurable water use. With real-time soil moisture data, farmers can adjust irrigation schedules and volumes based on actual crop needs, thus avoiding water waste and preventing over-irrigation, which can damage soil structure. In addition to efficient resource use, this system also reduces the carbon footprint by eliminating the need for uncontrolled fuel-based water pumps. Ecologically, this approach supports environmental conservation, maintains soil quality, and increases long-term productivity without exploiting natural resources. Socially, this technology paves the way for more climate-adaptive agricultural practices and can serve as an educational model for a younger generation of farmers who are more open to innovation. Thus, this system is an integral part of the transformation towards smart agriculture that is inclusive, efficient, and environmentally sound (Erlinnawati & Purwanto, 2024).

This research can serve as a strategic starting point for developing other smart agricultural systems that are affordable and applicable, especially for small and medium-sized farmers in rural areas. With a simple yet functional technological approach, this study demonstrates that IoT adoption does not have to be expensive or complex. The resulting system findings and design can be replicated and adapted to monitor other aspects of agriculture, such as air temperature, soil pH levels, and micro-weather predictions. This opens up opportunities for further collaborative research between researchers, technology developers, and farming communities to create solutions based on real-world needs. As a pioneering study, this research's contribution lies not only in the technical aspects, but also in how technology can be adapted socially and culturally to strengthen food security and sustainable agriculture in the future.

CONCLUSION

The IoT-based soil moisture monitoring system was successfully designed and implemented, providing real-time data that can be accessed remotely through digital devices, and has been proven to improve water use efficiency in irrigation activities because farmers can make decisions based on actual data, not just estimates or intuition. The system is designed to be simple and easy to use, thus enabling adoption by smallholder farmers and users with limited technological knowledge. However, there are technical challenges that need to be overcome, such as internet network stability and the need for sensor protection from extreme conditions in the field. This research makes a significant contribution to the development of small-scale smart farming systems and opens up opportunities for broader application of IoT technology in the agricultural sector towards more efficient, precise, and sustainable practices.

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