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Internet of Things Implementation Framework for Marginal Land Agriculture in Indonesia: Challenge Analysis and Adaptive Strategies

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ABSTRACT

The deployment of Internet of Things (IoT) in agriculture has enabled data-driven decision-making and resource optimization; however, its application in marginal agricultural environments remains limited by fragmented system design and lack of context-aware integration. This study proposes a taxonomy-driven conceptual framework for IoT implementation in marginal agriculture, addressing multi-dimensional constraints specific to the Indonesian context. A qualitative conceptual methodology is employed using a structured literature review based on a rapid review strategy. Relevant studies (2019–2026) are systematically selected and analyzed using directed thematic analysis across five dimensions: technical, communication, energy, environmental, and social. A taxonomy analysis is subsequently constructed to organize existing research, identify dominant design patterns, and expose structural gaps in current IoT architectures. The results reveal a strong bias toward isolated optimization of sensing and communication layers, with limited consideration of cross- layer integration, energy-aware operation, environmental adaptability, and user-centric design. These findings indicate the absence of a unified architectural model capable of addressing the constraints of marginal agricultural systems. To overcome these limitations, this study introduces a multi-layer IoT framework comprising sensing, communication, energy management, data analytics, and application layers. The framework emphasizes cross-layer interaction, adaptive resource management, and contextual decision support, enabling robust operation under limited infrastructure, variable environmental conditions, and low technology adoption settings. The novelty of this study lies in the integration of taxonomy analysis and multi-layer system design to construct a context- aware IoT framework that captures the complexity of marginal agricultural environments. This framework provides a scalable and adaptive reference model for future empirical validation and practical deployment of IoT-based smart agriculture systems in marginal environments.

INTRODUCTION

Marginal land farming is a strategic challenge in developing the agricultural sector in Indonesia. Marginal land is generally characterized by limited soil fertility, limited water availability, and unfavorable environmental conditions, such as steep topography and high salinity levels (Grover et al., 2024; The State of the World's Land and Water Resources for Food and Agriculture 2021 Systems at Breaking Point, 2022). These conditions directly impact low productivity and yield stability, ultimately impacting farmer welfare and national food security (Statistics, 2023). Furthermore, increasing food demand due to population growth demands technological innovations capable of optimizing the sustainable use of marginal land (Canton, 2021; Herforth et al., 2020).

The development of Internet of Things (IoT) technology opens up significant opportunities to increase the efficiency and productivity of the agricultural sector through the concept of precision agriculture (Wolfert et al., 2017; Q. Zhang, 2015). This technology enables the integration of various sensors to monitor environmental conditions in real time, such as soil moisture, temperature, and acidity (pH), enabling more accurate and data driven decision making (Ahmed et al., 2023; Borah et al., 2026). Numerous studies have shown that IoT implementation can improve the efficiency of resource use, such as water and fertilizer, and reduce the risk of crop failure (Abdollahi et al., 2021; Ojha et al., 2021).

However, the application of IoT to marginal land agriculture in Indonesia still faces various complex challenges. Limited communication infrastructure in remote areas, high energy consumption of IoT devices, and relatively high initial investment costs are major barriers to the adoption of this technology (Darmawan & Faisol, 2025a; Selvia et al., 2025; Widiastono et al., 2026). Furthermore, environmental factors such as extreme geographic conditions and high weather variability also impact the reliability of IoT systems (Adhy et al., 2025; Darmawan & Faisol, 2025b; Hadi et al., 2025). From a social perspective, low technological literacy among farmers and limited access to digital technology also hinder optimal implementation (Hidayati et al., 2025).

Several previous studies have examined the application of IoT in the agricultural sector, but most have focused on technical aspects or implementation in relatively ideal land conditions (Mowla et al., 2023; Nauli, 2025; Thilakarathne et al., 2021, 2025). Studies specifically addressing IoT implementation on marginal land, particularly in the Indonesian context, are still limited. Furthermore, the approaches used tend to be partial and fail to integrate various important dimensions, such as technical, communication, energy, environmental, and social aspects, within a comprehensive framework (Effah et al., 2023; Megawati, 2021; Rahayu, 2025).

This situation indicates a significant research gap, namely the absence of a holistic approach that integrates multiple dimensions while considering the specific characteristics of marginal land agriculture in Indonesia. Existing studies generally focus on isolated technical aspects and often overlook the interconnected challenges related to communication infrastructure, energy availability, environmental conditions, and social readiness. Therefore, there is a need for an IoT implementation framework that not only addresses technological requirements but also adapts to environmental constraints and user limitations. Based on this gap, the present study aims to analyze the challenges of IoT implementation in marginal land agriculture in Indonesia and formulate applicable adaptive strategies. Furthermore, this study proposes a multidimensional IoT implementation framework that integrates technical, communication, energy, environmental, and social aspects to support sustainable and effective technology adoption. The primary contribution of this research is the development of an adaptive and context-sensitive framework that provides practical guidance for implementing IoT solutions in the unique conditions of Indonesia's marginal agricultural lands.

The proposed framework not only integrates various technological components but also considers environmental and social factors as crucial for successful implementation. Therefore, this research is expected to provide theoretical contributions to the development of IoT concepts in the agricultural sector, as well as practical contributions as a reference for stakeholders in designing more effective technological solutions.

RESEARCH METHODS

This study employed a qualitative conceptual approach supported by a Systematic Literature Review (SLR) conducted using a rapid review strategy. The SLR approach was selected to ensure a transparent, systematic, and reproducible process for identifying, evaluating, and synthesizing existing knowledge related to the implementation of Internet of Things (IoT) technologies in marginal land agriculture. The rapid review strategy was adopted to streamline the review process while maintaining methodological rigor, allowing the study to efficiently capture recent developments and emerging trends in the field.

The review process followed four main stages adapted from established SLR guidelines, including planning, literature identification, study selection and analysis, conceptual synthesis, and framework validation, as illustrated in Figure 1. This methodological flow provides a structured pathway from problem identification to the development and validation of the proposed IoT implementation framework.

The first stage involved problem identification and literature retrieval. Research questions were formulated to explore the challenges, enabling factors, and implementation strategies of IoT in marginal land agriculture. Literature searches were conducted using several reputable scientific databases, including Google Scholar, IEEE Xplore, ScienceDirect, and SpringerLink. The search process employed combinations of keywords such as "Internet of Things agriculture," "smart farming," "precision agriculture," "marginal land," "resource-constrained agriculture," and "energy-efficient IoT." To ensure the relevance and recency of the findings, only publications published between 2019 and 2026 were considered. Inclusion criteria consisted of peer-reviewed journal articles, conference papers, and review studies discussing IoT applications in agriculture, smart farming systems, wireless communication technologies, energy management, environmental monitoring, and technology adoption. Studies not directly related to agricultural IoT implementation or lacking sufficient methodological information were excluded.

The second stage consisted of literature screening, selection, classification, and thematic analysis. Duplicate records and irrelevant studies were removed through a screening process based on titles, abstracts, and full-text evaluations. Selected studies were then categorized into five analytical dimensions: technical, communication, energy, environmental, and social aspects. A directed thematic analysis approach was employed to identify recurring themes, implementation challenges, solution strategies, and research trends. In addition, a research gap analysis was conducted to identify limitations in existing studies, particularly the lack of multidimensional integration and the limited adaptability of IoT architectures to marginal land conditions.

The third stage focused on conceptual synthesis and framework development. Findings from the thematic analysis were integrated using a taxonomy-based synthesis approach to map interrelationships among the identified dimensions. This process facilitated the identification of common architectural patterns, critical success factors, and adaptive mechanisms reported in the literature. The synthesized findings served as the foundation for designing a multidimensional IoT implementation framework comprising five interconnected layers: sensing layer, communication layer, energy management layer, data analytics layer, and application layer.

The fourth stage involved conceptual validation of the proposed framework. Validation was performed through logical and comparative analysis rather than empirical testing. Logical validation was conducted to assess the consistency and coherence of relationships among framework components, while comparative validation involved benchmarking the proposed framework against existing IoT architectures and conceptual models reported in previous studies. This validation process aimed to ensure that the proposed framework is comprehensive, adaptive, and capable of addressing the multidimensional challenges associated with IoT implementation in Indonesia’s marginal land agriculture.

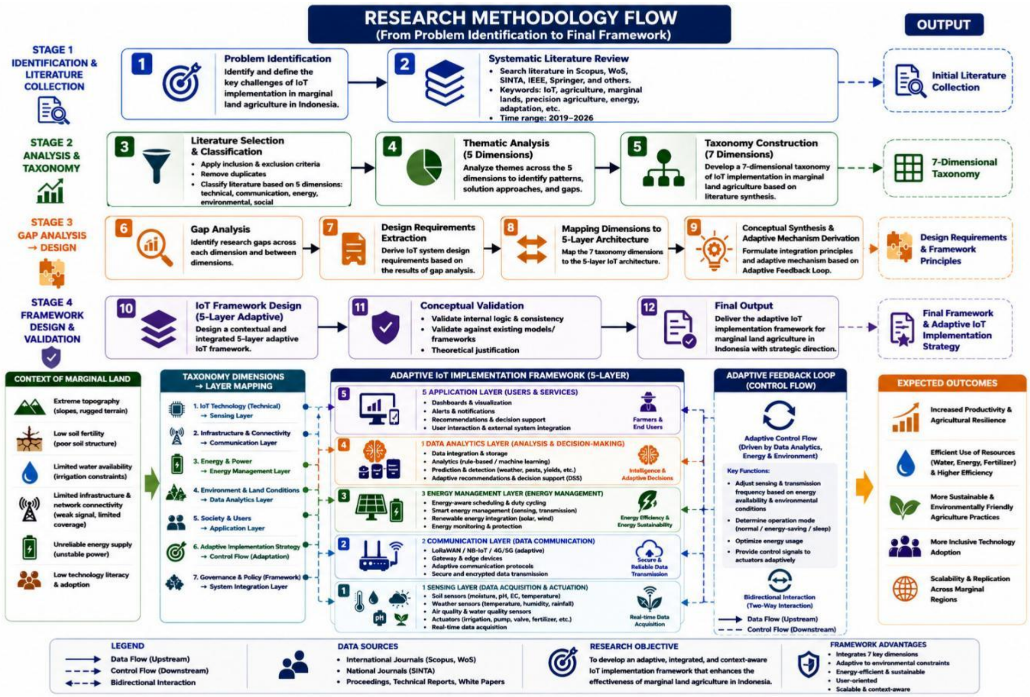

Figure 1. Research Methodology Flow for Designing an IoT Implementation Framework for Marginal Land Agriculture in Indonesia

As shown in Figure 1, each stage of this research produces outputs that serve as the basis for the next stage, from problem formulation, classified literature collection, challenge mapping, research gap identification, to framework design and validation. Thus, this methodological flow is not only systematic but also ensures traceability throughout the research process. The results of each stage form the basis for compiling the taxonomy, identifying research gaps, and designing the framework, which are discussed systematically in the results and discussion sections.

RESULTS AND DISCUSSION

Literature Synthesis and IoT Taxonomy in Marginal Land Agriculture

To gain a structured understanding of the development of IoT research in marginal land agriculture, this study developed a taxonomy based on literature synthesis, as shown in Figure 2. This taxonomy serves as an analytical framework for systematically organizing the literature and identifying research patterns and gaps. Unlike conventional classification approaches, the proposed taxonomy not only groups the literature by topic but also integrates four main elements: research focus, issues/challenges, key contributions, and research gaps within each dimension. This approach allows for a more comprehensive analysis of the existing research structure.

As shown in Figure 2, the literature is classified into seven main dimensions:

1. Iot technology (Technical),
2. Infrastructure and connectivity,
3. Energy and power,
4. Environment and marginal land conditions,
5. Social and user,
6. Adaptive implementation strategies, and
7. Framework

The analysis shows that research distribution is uneven across dimensions. The technical and connectivity dimensions dominate most studies, particularly in the development of sensor systems, IoT devices, and communication technologies such as LoRa and cellular networks. Conversely, the energy, environmental, and social dimensions remain relatively underexplored and tend to be discussed fragmentarily.

Furthermore, most research focuses on optimizing individual components without considering integration across dimensions. Studies on the communication aspect, for example, are generally not linked to energy efficiency strategies, while research on the environmental dimension has not yet been integrated with data-driven adaptive analytical mechanisms. This demonstrates the limitations of a holistic approach to IoT system design for marginal land.

Furthermore, the dimensions of adaptive implementation strategies and frameworks indicate that most proposed solutions fail to fully accommodate the complexities of marginal land conditions. Existing approaches remain sectoral and fail to integrate technical, environmental, energy, and social factors into a single, integrated system.

Thus, the taxonomy generated in this study serves not only as a classification tool but also as an analytical instrument to identify dominant patterns, relationships between dimensions, and open research areas. These findings form the basis for identifying research gaps and designing an adaptive IoT framework, discussed in the following section. This taxonomy serves as a conceptual foundation for bridging the gap between fragmented technical approaches and the need to implement integrated IoT systems in marginal agricultural environments.

Research Gap Identification

Based on the results of the literature synthesis and taxonomy analysis, as shown in Figure 2, IoT research in marginal land agriculture shows a development pattern that is still fragmented and not yet systemically integrated. The identified research gaps are not only partial in each dimension but also reflect limitations in building linkages between system components as a whole.

In general, the main gaps identified can be categorized into four fundamental aspects. First, limited integration across system dimensions. Most research still focuses on optimizing individual components, such as sensors or communications, without considering the interactions between layers, particularly the relationship between energy consumption, environmental conditions, and user needs. This results in solutions that are less adaptable to real-world conditions.

Second, the low level of system adaptability to the characteristics of marginal land. Conditions such as limited infrastructure, high environmental variability, and limited energy sources have not been fully accommodated in existing IoT system designs. Most approaches still assume ideal conditions, making them less relevant for implementation in marginal environments.

Third, limitations in utilizing data analytics for adaptive decision-making. Although some studies have adopted a data-driven approach, the integration between sensing data, analytics, and system control mechanisms remains suboptimal. As a result, systems are unable to make real-time operational adjustments based on changing environmental conditions and resource availability.

Fourth, there is a lack of attention to sustainability and user adoption. The energy and social dimensions, as seen in Figure 2, remain relatively underexplored compared to the technical and communication dimensions. This indicates that most studies have not considered energy efficiency and user acceptance as integral components of the system.

Overall, these gaps demonstrate the need for an approach that holistically integrates various dimensions while adapting to environmental and user constraints. Therefore, an IoT implementation framework is needed that not only focuses on the technological aspect but also accommodates cross-layer interactions, energy efficiency, and context-based decision-making mechanisms. This need forms the basis for designing the adaptive IoT framework proposed in the next section.

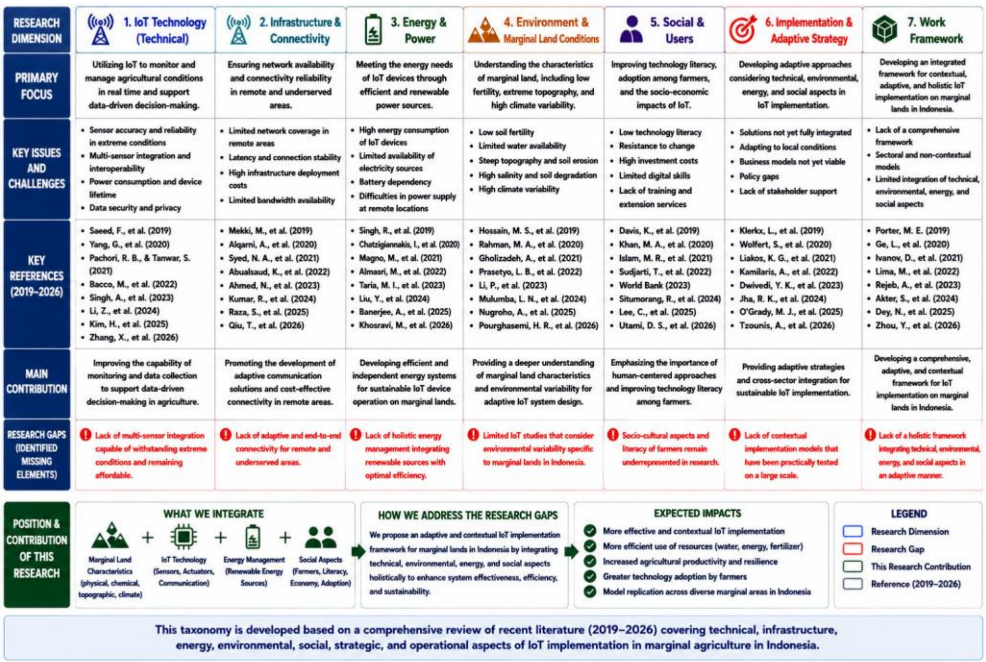

Figure 2. Taxonomy diagram of Internet of Things (IoT) implementation for marginal agriculture in Indonesia, highlighting key research dimensions, major challenges, state-of-the-art references (2019–2026), research gaps, and the proposed adaptive and integrated framework

IoT Implementation Framework for Marginal Land Agriculture

Based on the results of the taxonomy analysis and the identification of research gaps, this study proposes an Internet of Things (IoT) implementation framework systematically designed to address the limitations of integration, adaptability, and sustainability in marginal land agriculture. Unlike previous approaches, which tend to be partial and fragmented, this framework adopts a multi-layered architecture that integrates various system dimensions and supports context-based adaptation mechanisms.

As shown in Figure 3, the proposed framework consists of five main layers: the sensing layer, communication layer, energy management layer, data analytics layer, and application layer. Each layer not only functions independently but is also interconnected through data flow and control flow mechanisms that form an adaptive feedback loop. This mechanism allows the system to dynamically adjust operations based on environmental conditions, energy availability, and user needs.

The sensing layer plays a role in real-time acquisition of environmental data, such as soil moisture, temperature, pH, and other weather parameters. The collected data is then transmitted through the communication layer using protocols that adapt to infrastructure conditions, such as LoRa for remote areas or cellular networks for areas with better coverage This approach ensures reliable data transmission under limited network conditions.

The energy management layer is a key component in supporting system sustainability, particularly in environments with limited energy resources. This layer optimizes power consumption through duty cycling mechanisms, energy-aware scheduling, and the integration of renewable energy sources such as solar panels. Furthermore, this layer interacts with the sensing and communication layers to adaptively regulate the frequency of data collection and transmission based on available energy conditions.

The data analytics layer serves as the central processing and decision-making center within the system. Collected data is processed using rule-based analytical approaches and simple machine learning to generate relevant and contextual information. The results of this analysis are used to provide action recommendations, such as irrigation or fertilization settings, and send control signals back to the lower layers as part of a feedback loop mechanism.

The application layer provides an interaction interface for end users, particularly farmers, in the form of a web-based dashboard or mobile application. The interface design takes into account usability and limited technological literacy, ensuring that the information presented is simple, intuitive, and easy to understand. This layer also plays a role in delivering notifications, warnings, and action recommendations based on the results of system analysis.

Overall, the proposed framework integrates data and control flows into a single, unified system, enabling real-time adaptation to environmental dynamics, energy constraints, and user characteristics. This approach makes the framework not only modular and scalable, but also contextual and sustainability-oriented.

Compared to conventional IoT frameworks, which are generally linear and less adaptive, the approach proposed in this study emphasizes cross-layer integration through adaptive control mechanisms based on energy and environmental conditions. This integration enables the system to operate efficiently and reliably in marginal land areas with limited infrastructure and resources.

Furthermore, this framework provides a flexible basis for further development, both in the form of network simulations (e.g., using NS-3) and device-based prototype implementations such as ESP32 and LoRa. This opens up opportunities for empirical validation and system performance testing in future research.

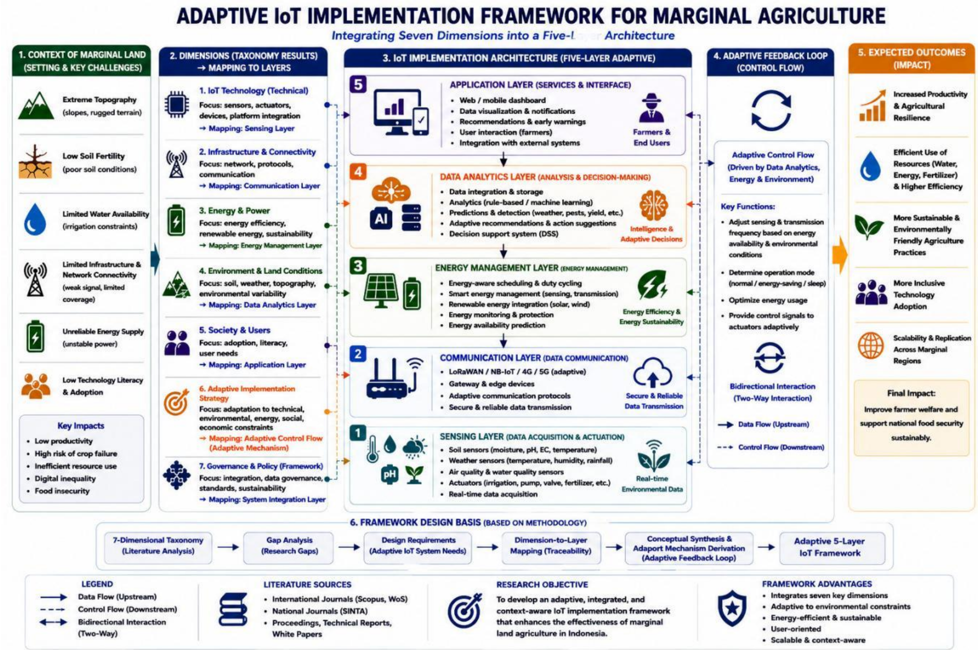

Figure 3. Adaptive Internet of Things (IoT) Implementation Framework Based on 7-Dimensional Integration in a 5-Layer Architecture for Marginal Land Agriculture in Indonesia

Discussion and Research Contribution

The framework proposed in this study significantly addresses the limitations of previous IoT approaches, which tended to be partial and fragmented. Unlike previous studies, which generally focused on a single dimension, such as sensor development or communication optimization, this framework integrates five key dimensions technical, communication, energy, environmental, and social into a unified and adaptive system architecture.

Conceptually, the primary contribution of this research lies in the integration of taxonomy analysis and multi-layer architecture design. The developed taxonomy serves not only as a literature classification tool but also as an analytical basis for identifying dominant patterns and research gaps. This integration enables the design of a framework that is more focused, evidence-based, and relevant to the real-world conditions of marginal land agriculture.

In terms of system architecture, the proposed framework introduces cross-layer interaction mechanisms through a combination of data flow and adaptive control flow. This approach differs from conventional IoT architectures, which are generally linear and less responsive to changing environmental conditions. With a feedback loop mechanism between the data analytics layer and the layers below, the system can dynamically adjust operational parameters such as sensing frequency and data transmission based on energy and environmental conditions.

Furthermore, the integration of the energy management layer as a core component within the architecture is a crucial contribution to supporting system sustainability. Most previous research has only addressed energy efficiency at the device level, without integrating it into the overall system design. In this framework, energy management serves not only as a support but also as a driver of system adaptability, particularly in resource-constrained environments.

From an implementation perspective, this framework also accommodates social aspects through a user-oriented application layer design. This is crucial given the low level of technological literacy among farmers in marginal land areas. Therefore, the proposed framework focuses not only on technical aspects but also considers technology adoption as an integral part of the system.

The theoretical implications of this research lie in the development of a holistic and contextual IoT conceptual model, capable of bridging the gap between technical approaches and implementation needs in the field. Meanwhile, the practical implications include providing a reference model that researchers and practitioners can use to design adaptive, efficient, and sustainable IoT systems in marginal land agricultural environments.

However, this research still has limitations. The proposed framework is conceptual in nature and has not undergone direct empirical validation in the field. Furthermore, the analytical model used in the data analytics layer is still generic and does not accommodate the specific complexity of agricultural data. Therefore, further research is needed to develop a system prototype and conduct simulation-based testing and real-world implementations to quantitatively evaluate the framework's performance and reliability. Thus, this research not only contributes in the form of a conceptual framework, but also opens up the direction of further research towards the development of an agricultural IoT system that is more adaptive integrated, and ready to be implemented in marginal land conditions in Indonesia.

CONCLUSION

The IoT implementation framework proposed in this study successfully represents the results of literature synthesis and taxonomy analysis into an integrated and adaptive conceptual model. This framework combines seven key dimensions: technical, infrastructure, energy, environmental, social, adaptive strategies, and frameworks, which collectively reflect the complexity of systems in marginal land agriculture.

Furthermore, this framework aligns with a layered architectural approach consisting of sensing, communication, energy management, data analytics, and application layers, thus bridging the gap between fragmented technical approaches and holistic implementation needs. The integration between dimensions and layers enables the system to operate adaptively to infrastructure limitations, environmental variability, and user characteristics.

Thus, the proposed framework is not only conceptual but also provides a strong foundation for the development of more efficient, sustainable, and contextual agricultural IoT systems in marginal land environments.

RECOMMENDATIONS

1. Further development of the data analytics layer component is necessary by integrating machine learning or artificial intelligence methods to improve the system's ability to predict and make adaptive decisions in real time.
2. Empirical validation through prototype implementation or simulation is needed to test the framework's performance in real-world conditions, particularly in terms of energy efficiency, communication reliability, and system adaptability.
3. Strengthening the feedback loop mechanism between layers is necessary to ensure the system is capable of dynamically implementing adaptive control based on environmental conditions and resource availability.
4. Further studies on social aspects and technology adoption models are needed to ensure that the resulting solution is not only technically feasible but also widely accepted and used by farmers.

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