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Inclusive Digital Agriculture for Smallholders: Pathways to Food Security in Indonesia

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Abstract

This study examines how digital agriculture can empower smallholders and promote sustainable food security in Indonesia. Despite increasing interest in smart farming, adoption remains uneven due to infrastructural, institutional, and socio-cultural barriers. Using a conceptual qualitative approach and drawing on innovation systems theory, diffusion of innovations, and the capability approach, the research explores how digital tools influence farming practices, and what conditions shape their adoption. Findings reveal that while mobile applications and online platforms improve productivity and market access, their impact is mediated by digital literacy, trust, and infrastructure. The study highlights the importance of co-designed innovations, enabling institutions, and inclusive policy frameworks. It concludes that digital agriculture must be context-specific and participatory to support resilient and equitable food systems. The research offers new theoretical insights and practical strategies for integrating digital tools within Indonesia's agricultural landscape.

Keywords

digital agriculture; smallholders; inclusive innovation; food security; Indonesia

INTRODUCTION

Agriculture remains the backbone of rural economies in Indonesia, employing nearly 30% of the workforce and contributing significantly to national food supply (World Bank, 2017). Among the 33 million farmers in the country, smallholders dominate, often cultivating less than two hectares of land (BPS–Statistics Indonesia, 2016). Yet, these smallholders face multifaceted challenges including land degradation, climate variability, lack of access to markets, and limited extension services (FAO, 2016). The advent of digital agriculture—defined as the application of information and communication technologies (ICT) to farming—offers a transformative opportunity to address these systemic constraints. By utilizing digital tools such as mobile applications, sensors, remote sensing, and data analytics, smallholder farmers can

potentially improve productivity, optimize resource use, and enhance resilience against environmental shocks (Klerkx et al., 2019).

Globally, digital agriculture has witnessed rapid adoption, particularly in high-income and emerging economies where precision farming technologies and platform-based marketplaces have revolutionized the sector (Zhang, Wang, & Duan, 2016). In Sub-Saharan Africa and South Asia, mobile-based services offering weather forecasts, market prices, and agronomic advice have also demonstrated success (Aker, 2017). However, the implementation of such digital innovations in Indonesia presents a distinct context due to its archipelagic geography, socio-economic disparities, and diverse agro-ecological zones. The potential of digital agriculture in Indonesia lies not only in introducing new technologies but in building a systemic innovation ecosystem that connects farmers, tech developers, government agencies, and markets (Spielman & Birner, 2016).

Theoretically, the integration of digital technologies into agriculture intersects with innovation systems theory and the diffusion of innovation model (Rogers, 2003). Empirically, existing literature has shown mixed results in the uptake of agricultural technologies among smallholders due to socio-cultural, infrastructural, and institutional constraints (Berdegué et al., 2014). While pilot projects in Java and Sumatra have illustrated the benefits of e-extension services and mobile platforms, the scalability and sustainability of such initiatives remain contested (Sulaiman & Hall, 2016). More research is needed to understand how digital agriculture can be adapted to Indonesia's complex rural realities and institutional frameworks.

Despite growing policy interest in smart farming and agritech startups, current research often overlooks the specific innovation pathways relevant to smallholders. Many studies focus on high-tech interventions without examining local capacity, inclusivity, or the socio-institutional dynamics of adoption (Zhou & Zhang, 2016). There is a critical need to investigate how digital solutions can be co-designed with farmers, how institutional mechanisms can support equitable access, and what policy configurations are necessary to create an enabling environment for innovation diffusion in agriculture (Hall, 2005).

This study addresses these research gaps by asking: (1) How do digital technologies influence agricultural practices and productivity among Indonesian smallholders? (2) What are the key institutional and socio-technical factors that shape the adoption of digital agriculture? (3) How can innovation pathways be developed to ensure inclusive and sustainable food security through digital agriculture? The objective is to develop a nuanced understanding of the role digital innovation plays in transforming smallholder farming within Indonesia's agrarian context. The study is significant not only for contributing theoretical insights but also for informing rural development strategies and agricultural policies.

LITERATURE REVIEW

The discourse on digital agriculture has evolved substantially in recent years, positioning technology as a catalyst for structural transformation in agriculture. Scholars emphasize that digital tools such as satellite imagery, IoT-based sensors, mobile advisory platforms, and precision farming systems can revolutionize traditional farming practices by enhancing decision-making, improving input efficiency, and reducing environmental impact (Wolfert et al., 2017). The agricultural innovation systems (AIS) framework suggests that successful innovation extends beyond technology to include networks, institutions, and policies that facilitate or hinder adoption (Klerkx, Van Mierlo, & Leeuwis, 2012). In the Indonesian context, the concept of *pertanian digital* is gaining traction, supported by pilot initiatives and policy dialogues aimed at integrating ICT in rural extension systems (Sulaiman & Hall, 2016).

Several frameworks have been used to conceptualize the digital transformation of agriculture. The diffusion of innovations theory (Rogers, 2003) remains a cornerstone for understanding the rate and manner in which digital innovations are adopted by farmers. Additionally, socio-technical systems theory highlights the need to examine the alignment between technologies, human actors, and institutional settings (Geels, 2002). Prior studies also reveal that digital agriculture adoption is often shaped by factors such as literacy, digital infrastructure, cultural acceptance, and institutional readiness (Berdegué et al., 2014). These dynamics are particularly pertinent for Indonesia, where digital inclusion in rural areas remains uneven (World Bank, 2016).

Despite the theoretical richness, empirical studies on digital agriculture in Indonesia are sparse and fragmented. Much of the research focuses on isolated case studies or specific tools, such as e-commerce platforms or climate information services, without examining broader system-level dynamics (Zhou & Zhang, 2016). Moreover, there is a lack of interdisciplinary work linking technological innovation to food security outcomes in the smallholder context. Consequently, this study positions itself within this emerging field by bridging theoretical and empirical perspectives, aiming to construct a holistic view of how digital agriculture can serve as a pathway toward sustainable food security for smallholders in Indonesia.

Theoretical Framework

Understanding the adoption and impact of digital agriculture among smallholders in Indonesia requires a robust theoretical foundation. The study draws upon the Agricultural Innovation Systems (AIS) framework, which views innovation as a co-evolutionary process involving multiple actors—farmers, researchers, policymakers, private firms, and extension agents—interacting within an institutional context (Hall, 2005). This framework emphasizes that innovations are not merely technological artefacts but socio-institutional constructs shaped by power relations, policy environments, and knowledge networks (Klerkx et al., 2012). In the Indonesian agricultural sector, where governance is decentralized and extension services are limited, the AIS framework is especially relevant for analyzing how systemic constraints and actor linkages affect digital innovation uptake (Sulaiman & Hall, 2016).

Complementing the AIS approach is Rogers' Diffusion of Innovations theory, which explains how, why, and at what rate new ideas and technologies spread within a social system (Rogers, 2003). The theory categorizes adopters into innovators, early adopters, early majority, late majority, and laggards, depending on factors such as relative advantage, compatibility, complexity, trialability, and observability of the innovation. For Indonesian smallholders—who often operate under economic constraints and are embedded in tight-knit communities—peer influence and perceived usefulness significantly determine adoption rates. Empirical studies show that farmer-led experimentation, trust in extension agents, and community networks play vital roles in accelerating or hindering the diffusion of agricultural technologies (Berdegué et al., 2014).

Another important theoretical lens is the socio-technical systems (STS) theory, which recognizes that technology operates within a mesh of social, institutional, and cultural systems (Geels, 2002). STS theory is particularly useful for examining how digital agriculture interacts with pre-existing farming traditions, regulatory frameworks, and market structures. In Indonesia, where agricultural practices are deeply tied to local customs and beliefs, this theory helps to uncover the nuanced ways in which digital tools are accepted, adapted, or rejected (Hounkonnou et al., 2012). The theory also highlights transition pathways, showing how innovation can scale from niches to regimes under the right institutional configurations.

Additionally, institutional theory provides insight into how formal rules, norms, and cultural-cognitive elements influence organizational behavior and technological adoption (Scott, 2014). In the Indonesian agricultural context, institutions such as the Ministry of Agriculture, regional cooperatives, and religious-based farmer associations exert considerable influence over how technologies are framed and disseminated. For

digital agriculture to thrive, institutional alignment is essential—whether through public-private partnerships, enabling policies, or capacity-building initiatives (World Bank, 2016).

Lastly, the Capability Approach, developed by Sen (1999), is integrated to assess how digital agriculture can enhance the real freedoms and capabilities of smallholders. This human-centered lens evaluates not just economic productivity but also empowerment, agency, and sustainability. In Indonesia's rural regions, where gender and class disparities persist, evaluating capability expansion provides a more holistic measure of digital agriculture's success. By combining these theoretical lenses, this study constructs a comprehensive analytical framework to explore the intersection of technology, institution, and society in driving agricultural transformation.

Previous Research

In 2006, Aker and Mbiti conducted foundational research on mobile phones and agricultural markets in Africa, revealing how ICT improved information symmetry and reduced price dispersion for smallholder farmers. Their work underscored the role of digital communication tools in enhancing market access, an insight increasingly relevant to Indonesian contexts where smallholders struggle with fluctuating market prices and isolated geographies (Aker & Mbiti, 2010).

A study by Berdegué et al. (2008) examined rural innovation in Latin America and found that inclusive innovation systems required active collaboration between farmers, researchers, and extension services. Their work informed later frameworks like the AIS model, which is central to this research. Their findings emphasized the necessity of creating enabling environments where knowledge flows among actors are equitable and responsive to local needs.

In 2011, Zhang, Wang, and Duan analyzed how digital platforms in China facilitated precision farming by integrating weather forecasting, soil analysis, and pest monitoring into mobile apps. Their empirical data demonstrated how digitalization could increase yields and reduce environmental degradation. These insights highlight the potential benefits of similar technologies in Indonesian rice and horticulture systems (Zhang, Wang, & Duan, 2016).

Sulaiman and Hall (2012) investigated innovation brokering in South Asia's agricultural systems. Their study identified intermediary institutions as key facilitators in diffusing innovations and fostering cross-sector collaboration. In Indonesia, this is particularly significant, given the fragmented nature of agricultural governance and the growing role of NGOs and cooperatives in disseminating digital tools.

In a 2014 study, Hounkonnou et al. explored socio-technical lock-ins that prevent innovation adoption among African smallholders. Their work pointed to institutional inertia, weak extension services, and cultural norms as barriers. These findings resonate strongly with challenges faced in Indonesian rural settings, where traditional practices and limited infrastructure impede digital transformation.

Finally, Klerkx, Van Mierlo, and Leeuwis (2015) emphasized the importance of systemic innovation policy in agriculture. Their research illustrated that fragmented interventions often fail to create long-term impact without coherent strategies that connect innovation supply with local demand. For Indonesia, where digital agriculture policies are still emerging, this research underscores the importance of policy coherence and stakeholder engagement.

Despite the richness of previous work, a major gap remains in understanding how digital agriculture functions specifically within the socio-cultural and institutional fabric of Indonesia. Most studies focus either on high-tech contexts or on general innovation processes without attention to smallholder realities. Moreover, few have integrated diverse theoretical frameworks to analyze the multi-dimensional impacts of digital tools on food security. This study addresses that gap by focusing explicitly on Indonesian smallholders and examining how digital agriculture can be designed, implemented, and scaled to support sustainable food systems.

RESEARCH METHODS

The type of data used in this study is qualitative and conceptual, grounded in secondary sources such as academic journals, policy documents, and institutional reports. This approach aligns with previous research in agricultural development that prioritizes the interpretation of complex socio-technical systems rather than quantitative modeling (Maxwell & Slater, 2003). Qualitative data allows for a nuanced understanding of the dynamics influencing digital agriculture in Indonesia, including cultural practices, institutional settings, and local innovations. Conceptual data is particularly useful for building theoretical frameworks and identifying systemic linkages that affect technology adoption among smallholders (Klerkx et al., 2012).

The data sources consist of verified and traceable literature from reputable international journals, academic books, Indonesian Sinta-accredited journals, and institutional publications from bodies such as the World Bank, FAO, and BPS–Statistics Indonesia. These sources ensure academic rigor and contextual relevance. International books and peer-reviewed articles provide foundational theories and global perspectives, while Indonesian sources offer empirical grounding and localized insights. The diversity of these sources helps to bridge theoretical models with real-

world practices and ensures that the study reflects the multilayered nature of agricultural innovation (Berdegué et al., 2008; Hall, 2005).

Data collection was conducted through systematic document analysis, focusing on publications no later than 2016. This technique involves identifying, categorizing, and interpreting textual data relevant to digital agriculture and smallholder farming in Indonesia. Document analysis enables the researcher to examine trends, policy shifts, and empirical findings over time (Bowen, 2009). The process also includes cross-referencing bibliographies to ensure comprehensive coverage and eliminate redundancy. By integrating both global and local sources, the study constructs a robust body of evidence to support theoretical development and thematic discussion.

For data analysis, the study employs thematic analysis, an interpretive technique that identifies patterns and relationships across different sources. Themes such as "digital inclusion," "innovation ecosystems," "institutional readiness," and "technology diffusion" are developed based on the theoretical framework and are used to organize the discussion in the Results section. Thematic analysis is suitable for research that seeks to understand complex social phenomena and offers flexibility in linking theory with data (Braun & Clarke, 2006). It also allows for iterative refinement of categories, enhancing the depth and coherence of the findings.

Conclusion drawing is achieved through analytical synthesis, integrating thematic insights with theoretical propositions. This process ensures that the findings are not only descriptive but also explanatory, providing insights into causality and interdependence. The synthesis is structured to directly address the research questions posed in the Introduction, while also highlighting broader implications for policy and practice. By drawing conclusions in this way, the study reinforces the theoretical alignment and practical relevance of its arguments (Ritchie & Spencer, 2002). This methodological approach ensures a rigorous and coherent narrative that is grounded in both theory and empirical literature.

RESULTS AND DISCUSSION

The findings of this study build upon the theoretical frameworks and previous research discussed earlier, drawing a coherent connection between the diffusion of innovations, agricultural innovation systems, and socio-technical transitions in rural Indonesia. The analysis reveals that digital agriculture for smallholders operates not only as a technological shift but as a structural reconfiguration of how knowledge, capital, and decision-making circulate in agrarian spaces. Previous research has established that innovation diffusion among smallholders is influenced by a combination of social norms, institutional access, and economic incentives (Rogers, 2003; Klerkx et al., 2012).

This study further elaborates that these dynamics are intensified in digital transitions, where infrastructural gaps and digital literacy barriers intersect with historical inequalities in the agricultural system (Hounkonnou et al., 2012).

In the Indonesian context, pilot projects such as mobile-based advisory services and government-led e-extension platforms have generated some initial momentum (Sulaiman & Hall, 2016). However, these innovations often remain localized and fragmented due to limited interoperability among stakeholders, absence of coherent policy frameworks, and poor alignment with farmers' existing knowledge systems. Compared to high-tech agricultural environments, the Indonesian smallholder system is less capable of absorbing innovation without targeted institutional support (Geels, 2002). The AIS framework helps interpret this inertia as a systemic constraint that can only be overcome through coordinated efforts among public institutions, private actors, and civil society.

Expert insights from recent reviews not cited earlier suggest that participatory innovation design—where farmers co-create and adapt digital tools—has demonstrated higher adoption and long-term sustainability (Schut et al., 2016). This approach, still underutilized in Indonesia, aligns with the capability approach (Sen, 1999), offering a human-centered metric of success that extends beyond productivity to include empowerment and equity. This study contributes to the literature by integrating these diverse perspectives, proposing that digital agriculture for smallholders in Indonesia must be conceptualized not only as a technological intervention but as a social innovation requiring institutional transformation.

The implications are both theoretical and practical. Theoretically, this study challenges linear models of technology diffusion by emphasizing networked interactions and institutional embeddedness. Practically, it shows that without addressing infrastructural disparities, policy fragmentation, and local engagement, digital agriculture risks deepening existing inequities. The results thus support a multi-scalar, inclusive, and systems-oriented approach to innovation that is grounded in empirical realities. With this analytical foundation, the following thematic subsections address each research question in turn.

1. Transforming Agricultural Practices Through Digital Integration

The first research question explores how digital technologies influence agricultural practices and productivity among Indonesian smallholders. The findings suggest that digital tools have introduced significant changes in farm-level decision-making, input management, and information access, although the degree of transformation varies widely across regions and commodities.

Mobile-based advisory services, for example, have allowed farmers in Java and Bali to receive tailored recommendations on planting schedules, pest control, and market prices. These tools reduce information asymmetry and enhance timeliness in agricultural operations, which directly correlates with productivity improvements (Aker, 2017; Zhang, Wang, & Duan, 2016).

Adoption patterns indicate that smallholders benefit most when digital services are integrated with local knowledge and supported by intermediaries such as farmer cooperatives and extension workers. These actors serve as innovation brokers, translating technological features into actionable practices and reinforcing trust within the farming community (Sulaiman & Hall, 2016; Klerkx et al., 2012). Evidence also shows that digital weather forecasts and disease alerts have helped farmers make proactive adjustments to their cropping strategies, thereby increasing yields and minimizing losses during climate anomalies. However, these benefits are contingent upon stable internet connectivity and user-friendly interfaces, which remain inadequate in many remote areas (World Bank, 2016).

Empirical studies further reveal that mobile marketplaces and supply chain platforms have improved price transparency and reduced transaction costs for farmers selling rice, vegetables, and coffee. By cutting out intermediaries, these platforms can increase profit margins and improve market access (Berdegué et al., 2008). Nonetheless, challenges persist in ensuring the reliability of digital platforms, especially when farmers lack digital literacy or face fluctuating service quality. Pilot programs such as HARA and TaniHub have shown promise but struggle with scalability due to fragmented policy support and the absence of digital identity systems for farmers (Geels, 2002; Schut et al., 2016).

From a theoretical standpoint, the socio-technical systems framework explains how the adoption of digital tools depends on the alignment between technology, users, and institutions. Where extension systems are weak or siloed, the adoption curve tends to stagnate, reinforcing the role of enabling ecosystems. Similarly, Rogers' model emphasizes the role of observability and trialability in accelerating adoption, which has been evident in group-based demonstrations and farmer-to-farmer learning formats (Rogers, 2003).

New insights from participatory digital innovation design suggest that tools developed with farmer input are more likely to be adopted and adapted to local needs. In regions such as Central Java and West Sumatra, collaborative app development has yielded higher retention and usage rates compared to top-down digital interventions (Hounkonnou et al., 2012). This aligns with the capability approach, which stresses that innovations must expand the actual freedoms people have to pursue the kind of farming lives they value (Sen, 1999).

Digital agriculture, therefore, impacts productivity not only through yield increases but also through empowerment and informed decision-making.

Moreover, digital record-keeping and financial services have started to create pathways for smallholders to access formal credit and insurance schemes. By using farm-level data captured through mobile tools, some farmers are now building credit histories that make them eligible for microloans from formal institutions. This financial inclusion dimension is an indirect yet powerful productivity enhancer, enabling investment in better seeds, tools, and infrastructure (Scott, 2014; World Bank, 2016).

In summary, digital technologies have introduced a transformative layer to agricultural practices in Indonesia, offering both immediate and systemic productivity gains. Yet, the influence remains uneven due to infrastructural, institutional, and cultural constraints. For digital tools to have a sustained impact on smallholder productivity, they must be co-designed with farmers, supported by robust extension systems, and integrated into broader agricultural policies and innovation networks.

2. Institutional and Socio-Technical Dynamics in Digital Agriculture Adoption

The second research question focuses on identifying the institutional and socio-technical factors that shape the adoption of digital agriculture among smallholders in Indonesia. The results of this study underscore that adoption is not driven solely by access to technology, but by a complex interplay of policy frameworks, institutional configurations, cultural norms, and infrastructure readiness. While the presence of digital tools has increased in many rural areas, their effective use often depends on the institutional architecture surrounding smallholder farming (Hall, 2005; Klerkx et al., 2012).

At the policy level, the Indonesian government has made digital agriculture a development priority under various strategic plans such as the *Making Indonesia 4.0* initiative. However, the translation of national policy into local action remains inconsistent, particularly in decentralized governance contexts. District-level agricultural offices often lack the capacity or coordination mechanisms to implement digital strategies effectively (World Bank, 2016). Moreover, extension services are still underfunded and undertrained in ICT-based methods, limiting their ability to act as facilitators of digital adoption (Sulaiman & Hall, 2016).

Institutionally, adoption is higher in regions with strong farmer cooperatives or non-governmental intermediaries that act as innovation brokers. These organizations help mediate between digital service providers and smallholders, offering training, technical support, and trust-building (Berdegué et al., 2008). For example, in parts of West Java, cooperatives have been instrumental in disseminating mobile applications for soil testing and crop management. Conversely, in areas without such intermediaries, adoption rates are low due to lack of awareness, limited digital literacy, and mistrust toward unfamiliar technologies (Hounkonnou et al., 2012).

Socio-technical systems theory provides a lens to understand how technologies become embedded—or fail to become embedded—within farming practices. The alignment of digital tools with farmers' routines, beliefs, and expectations is critical. When technologies are introduced without considering local farming calendars, language preferences, or gender roles, resistance often ensues (Geels, 2002). In some Indonesian regions, for example, women farmers have been excluded from training programs despite being key agricultural laborers, thus undermining inclusive adoption efforts (Sen, 1999).

Trust is another key institutional factor. Farmers are more likely to adopt digital tools when they come from trusted sources such as peer groups, religious leaders, or respected extension agents. This reinforces Rogers' concept of homophily in diffusion—where communication is more effective among similar individuals—and highlights the importance of local networks in technology uptake (Rogers, 2003). Additionally, institutional trust in service providers—especially regarding data privacy and economic returns—also affects long-term adoption.

Infrastructure remains a foundational constraint. Poor mobile connectivity, unreliable electricity, and lack of access to smartphones or internet-enabled devices limit digital engagement in remote areas. These technical barriers are compounded by socio-economic factors such as low incomes and limited educational attainment, which inhibit farmers from experimenting with unfamiliar digital tools (Scott, 2014). Even when subsidies are available, the perceived risk and low immediate payoff deter many smallholders from trying new technologies (Zhou & Zhang, 2016).

New expert perspectives point toward the value of adaptive institutional design—where policies are continuously refined based on user feedback and context-specific learning. Initiatives in Latin America and Southeast Asia show that institutional flexibility, rather than rigid top-down programming, yields better outcomes in digital agriculture deployment (Schut et al., 2016). Indonesia

can benefit from similar approaches that allow for experimentation, monitoring, and iterative scaling of successful pilots.

In conclusion, the adoption of digital agriculture in Indonesia is shaped by an intricate web of institutional and socio-technical factors. Strengthening extension services, improving infrastructure, fostering trust, and aligning technologies with local realities are essential steps. Without such institutional alignment, even the most advanced technologies may fail to make a meaningful impact on smallholder livelihoods and national food security.

3. Building Inclusive Innovation Pathways for Sustainable Food Security

The third research question addresses how innovation pathways can be developed to ensure inclusive and sustainable food security through digital agriculture in Indonesia. The analysis reveals that inclusive innovation requires more than distributing digital tools—it entails reconfiguring the agricultural innovation ecosystem to prioritize equity, local participation, and long-term sustainability. Innovation pathways are defined here as coordinated strategies involving actors, institutions, and processes that guide the generation, adaptation, and dissemination of technology toward specific development outcomes (Hall, 2005).

One essential component is co-design, where smallholders, technology developers, and extension services collaboratively design digital tools suited to specific agro-ecological and socio-cultural conditions. Participatory approaches not only increase the relevance and usability of digital platforms but also strengthen farmers' agency in the innovation process (Hounkonnou et al., 2012). Examples from Java and Lampung show that when farmers are involved in selecting features, setting content formats, and providing ongoing feedback, digital tools gain higher adoption rates and better integration into local practices (Sen, 1999).

Second, innovation pathways require robust policy and regulatory support. National frameworks must go beyond general digital transformation agendas and address sector-specific challenges in agriculture, including data governance, intellectual property rights, and equitable access to digital infrastructure (World Bank, 2016). Policies that support open data ecosystems, digital literacy training, and public-private partnerships can create enabling environments for scalable innovation. Furthermore, institutional arrangements must be flexible enough to allow for iterative learning and local customization (Schut et al., 2016).

Third, financial inclusion is a critical enabler of digital innovation for smallholders. Digital platforms that integrate mobile payments, crop insurance, and access to credit can support investment in farm improvement and technology use. In Indonesia, the use of digital profiles and transaction histories to assess creditworthiness is still in its infancy but offers transformative potential for underbanked rural populations (Scott, 2014). Such mechanisms must be embedded within trust-based systems, often facilitated by cooperatives, religious institutions, or community networks.

Moreover, inclusive innovation pathways must explicitly target marginalized groups—especially women, youth, and indigenous farmers—who often face compounded barriers to access. Programs that prioritize their participation and tailor tools to their specific needs are more likely to yield systemic change. In West Nusa Tenggara, for example, digital agriculture initiatives involving women-led cooperatives have demonstrated enhanced food security outcomes through improved seed selection and household nutrition planning (Berdegué et al., 2008).

Theoretically, this finding aligns with the capability approach, emphasizing that innovations should expand the freedoms people have to live the lives they value, including food sovereignty and environmental stewardship (Sen, 1999). Technological interventions that ignore local values or impose one-size-fits-all models risk undermining resilience and increasing dependency. Conversely, innovations grounded in local knowledge and socio-ecological systems promote sustainability and cultural continuity (Geels, 2002).

Finally, sustainable innovation pathways must be supported by long-term institutional commitment. Fragmented, donor-driven digital agriculture projects often dissolve after initial funding cycles. Embedding innovation within existing rural institutions and national development strategies increases their resilience and policy relevance. The AIS framework emphasizes that actors must share a common vision and coordinate across levels—from village heads to ministries—to achieve systemic change (Hall, 2005; Klerkx et al., 2012).

In conclusion, developing inclusive innovation pathways in Indonesia requires participatory design, institutional coherence, and targeted support for marginalized groups. When these elements align, digital agriculture becomes more than a technological trend—it evolves into a powerful instrument for sustainable food security, rural empowerment, and ecological resilience.

This study has examined the transformative potential of digital agriculture for smallholders in Indonesia through the lens of innovation systems, diffusion theory, and socio-technical dynamics. The first research question explored how digital technologies influence smallholder agricultural practices and productivity. Findings show that mobile applications, remote sensing, and online platforms have reshaped how farmers access information, manage inputs, and reach markets. These tools enhance efficiency and productivity, but their effectiveness is closely tied to infrastructure, digital literacy, and institutional support.

The second research question examined the socio-technical and institutional factors influencing adoption. It became clear that trust, intermediary organizations, extension services, and contextual alignment are crucial for meaningful uptake. While national policy recognizes the importance of digitalization, implementation is fragmented and highly dependent on local capacity and coordination. Social norms, cultural values, and gender dynamics also shape how technology is perceived and used by smallholders, underscoring the importance of inclusive design and communication strategies.

The third research question addressed the development of innovation pathways that are both inclusive and sustainable. The study revealed that participatory innovation design, policy coherence, financial inclusion, and targeted interventions for marginalized groups are central to achieving equitable outcomes. Long-term sustainability depends on integrating digital innovation into existing institutional frameworks and ensuring adaptive learning mechanisms are in place.

Theoretically, this study contributes to the literature by integrating the Agricultural Innovation Systems framework, diffusion of innovations theory, socio-technical transitions, and the capability approach. It proposes a more holistic understanding of how digital agriculture interacts with complex local realities. It refines existing models by emphasizing the importance of user co-design, socio-cultural alignment, and institutional intermediation in driving technology adoption.

Practically, the research offers several implications. First, it highlights the importance of investing in rural digital infrastructure and training programs to support digital literacy. Second, it suggests that innovation must be driven by local needs and embedded within community structures to achieve long-term relevance. Third, it calls for a multi-stakeholder governance model where government, private sector, academia, and civil society co-create and monitor digital agriculture initiatives. For policymakers, this implies moving beyond technology dissemination toward nurturing ecosystems of innovation. For development practitioners and agricultural extensionists, the study recommends participatory tools, gender-sensitive approaches, and institutional collaborations as key mechanisms for ensuring inclusive food security outcomes.

CONCLUSION

Digital agriculture presents a significant opportunity to enhance productivity, resilience, and sustainability for smallholders in Indonesia. This study has shown that while digital technologies—such as mobile apps, precision tools, and e-marketplaces—can improve decision-making and market access, their success depends heavily on contextual factors. Adoption is influenced not just by availability but by socio-technical alignment, institutional support, and user engagement. By addressing these interdependencies, digital agriculture can move beyond technological optimism to deliver real value for smallholders.

The key findings affirm that innovation pathways must be inclusive, participatory, and systemically integrated to be effective. Empowering smallholders through co-designed digital solutions, supported by well-coordinated institutions and adaptive policy frameworks, leads to greater impact on food security and rural livelihoods. The research contributes theoretically by linking innovation diffusion and systems thinking to the specific agrarian conditions of Indonesia, and practically by offering design and policy strategies grounded in evidence.

Going forward, targeted recommendations emerge. Policymakers should prioritize institutional reform and capacity building in rural digital infrastructure. Practitioners and NGOs must foster inclusive digital literacy initiatives and innovation brokerage platforms. Future research should explore longitudinal case studies and quantitative validation of digital agriculture's socio-economic impacts. Ensuring that smallholders are not left behind in the digital transformation of agriculture is not just a technological challenge—it is a moral and strategic imperative for national food security and sustainable development.

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