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Digital Agricultural Technology for Smallholder Farmers: Barriers and Opportunities in Indonesia

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ABSTRACT

Abstract

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The adoption of Digital Agricultural Technology (AgTech) has been widely promoted as a solution to enhance productivity, efficiency, and sustainability in Indonesia's agricultural sector. However, in regions dominated by smallholder farmers, such as West Java, Central Java, Yogyakarta, East Java, Bali, and Lampung, AgTech uptake remains limited due to infrastructural, economic, and institutional challenges. This study aims to explore the barriers and opportunities in AgTech adoption among smallholder farmers, cooperatives, and agritech stakeholders. Utilizing a qualitative research approach, data were collected through in-depth interviews and focus group discussions involving 85 participants from diverse agricultural settings. Thematic analysis and NVivo-assisted sentiment mapping were used to analyze stakeholder perspectives. Results reveal that AgTech adoption is progressing but uneven, with persistent challenges including limited digital literacy, unreliable internet and electricity, dependence on middlemen, and misalignment between infrastructure investment and training. Successful public-private partnerships (PPPs) and targeted training programs emerged as key enablers. The findings underscore the need for integrated strategies that combine technological infrastructure with localized capacity-building and financial support. This study contributes empirical insights for policymakers, agritech developers, and development agencies aiming to advance inclusive and sustainable digital transformation in Indonesia's agricultural landscape.

INTRODUCTION

The implementation of Digital Agricultural Technology (AgTech) has emerged as a critical strategy for enhancing productivity, operational efficiency, and long-term sustainability in the agricultural sector, particularly in the context of developing countries. AgTech encompasses a wide array of digital innovations and technologies, ranging from precision agriculture and Internet of Things (IoT)-enabled sensors to artificial intelligence (AI)-driven analytics and blockchain applications for supply chain transparency (Klerkx & Rose, 2020; Rotz et al., 2019). These tools enable more informed, data-driven decision-making, optimize the use of scarce resources such as water and fertilizers, and contribute to lowering input costs while improving the quality and quantity of agricultural yields (Wolfert et al., 2017).

In Indonesia, where the majority of agricultural production is driven by smallholder farmers cultivating less than two hectares of land, AgTech holds significant potential to enhance economic resilience, foster the development of smart farming practices, and strengthen food security at both household and national levels. However, the dissemination and adoption of AgTech among smallholder farmers remain uneven and are still in their early stages, constrained by structural, financial, institutional, and regulatory barriers. According to a report by M Corps, as cited in Sihombing et al. (2024), only approximately 4.5 million farmers in Indonesia, or 13.4% of the total farming population, have integrated internet-based technologies into their agricultural management practices. Meanwhile, the complexity of challenges in the national agricultural sector continues to grow, particularly due to the dominance of smallholder farmers in Indonesia's agrarian structure. Data from Statistics Indonesia, as cited in Sihombing et al. (2024), reveal that 72.19% of Indonesian farmers fall into the smallholder category, defined as those managing less than two hectares of land and earning no more than IDR 18.80 million annually.

The adoption of AgTech among smallholder farmers is shaped not only by technical and infrastructural factors but also by complex interactions involving economic, behavioral, and institutional dynamics. The digital divide in agriculture has long been recognized as a significant barrier to inclusive development, especially in rural and remote areas of developing countries (Reichardt et al., 2009). In Indonesia, this divide is evident through the unequal access to technological devices, unreliable internet connectivity, and limited electricity infrastructure, particularly in remote and underdeveloped regions (World Bank, 2021). These infrastructural limitations are exacerbated by the high initial investment costs of AgTech devices and ongoing maintenance or subscription fees. Such conditions hinder AgTech adoption among smallholder farmers, who often operate under financial constraints and exhibit risk aversion due to their vulnerability to price volatility and climate uncertainty (Klerkx & Rose, 2020).

Educational and generational disparities also play a critical role, as older farmers or those with limited formal education frequently lack the digital literacy necessary to operate complex technologies or utilize AI-based tools (Bu, 2024). This results in low technology utilization even when access is available. From an economic standpoint, transaction cost economics (TCE) posits that high costs associated with information search, negotiation, and contract enforcement can impede technology adoption, particularly in rural areas characterized by information asymmetries and inefficient supply chains (Sharma & Sharma, 2025). While intermediaries (middlemen) can reduce transaction costs by linking farmers to markets and offering logistical or financial support (Dimitri & Gardner, 2019), excessive dependence on these actors may create power imbalances and foster dependency through informal contracts (Touboulic, Chicksand, & Walker, 2014).

Behavioral factors also influence the landscape of technology adoption. Trust in partners—whether governmental agencies, private companies, or cooperatives—can reduce perceived risks and enhance farmers' willingness to adopt AgTech (Issa, et al., 2023; Yeo, M. L., & Keske, 2024). For instance, risk-averse farmers may hesitate to invest in digital tools

due to concerns over data privacy, market reliability, or uncertain economic returns, whereas risk-tolerant farmers may view AgTech as a long-term investment opportunity (Dadzie, et al., 2022). Moreover, the institutional and policy environment plays a substantial role in shaping technology adoption. Regulatory uncertainty, the absence of standardized data governance, and fragmented agricultural

policies, particularly under decentralized governance structures, create inconsistencies that deter private AgTech investments (Janssen et al., 2017). In response to these challenges, public-private partnerships (PPPs) have emerged as a promising mechanism to overcome multi-layered barriers by promoting collaboration, risk-sharing, and the facilitation of technology transfer (Birner & Resnick, 2010). Successful PPP models in countries such as India and Kenya have demonstrated this potential. However, in Indonesia, the effectiveness of PPPs remains limited due to bureaucratic inefficiencies, weak coordination, and inadequate regulatory frameworks (World Bank, 2021). These challenges underscore the need for empirical research grounded in real-world experiences and stakeholder engagement to better understand existing barriers and design context-specific strategies that promote inclusive and sustainable AgTech adoption across Indonesia's diverse agricultural landscape.

Previous studies on AgTech adoption have predominantly focused on the technological potential and efficiency gains offered by digital innovations in agriculture, often emphasizing large-scale or commercial farming contexts (Smith, 2024; Wong, et al., 2021). Mannari et al. (2024) explored the sociotechnical dimensions of digital agriculture, underlining the importance of user engagement and contextual adaptation. Meanwhile, Smidt & Jokonya (2022) and Drewry et al. (2019) highlighted the critical role of digital literacy gaps in shaping the adoption of agricultural technologies. In the Indonesian context, existing literature largely centers on pilot projects, digital infrastructure, and government policy roles; however, it remains limited in examining how smallholder farmers directly experience and navigate AgTech in practice. This study distinguishes itself by adopting a multi-sectoral, stakeholder-centered qualitative approach. It incorporates not only the perspectives of farmers but also those of AgTech developers, financial institutions, and policymakers across various regions. In contrast to previous research, this study emphasizes the intersection of structural, behavioral, and institutional barriers and aims to propose context-sensitive policy models and partnership frameworks that can facilitate inclusive AgTech adoption among smallholder farmers across agriculture, fisheries, and livestock sectors.

The research addresses a strategic issue concerning the adoption of agricultural digital technologies (AgTech) by smallholder farmers in Indonesia, highlighting the critical importance of context-specific understanding of the social, institutional, and infrastructural factors that influence their implementation dynamics. The novelty of this study lies in its regionally grounded qualitative methodology that captures regional variations in agricultural practices and innovation ecosystems while integrating cross-actor perspectives within the digital agriculture system, ranging from farmers, extension officers, AgTech enterprises, financial service providers, to policymakers. Furthermore, the study introduces a collaborative stakeholder framework intended to align incentives and minimize policy fragmentation, thereby fostering a more coherent and inclusive AgTech ecosystem. As such, the research contributes both theoretically and practically by enhancing our understanding of the key determinants that support successful digital transformation in Indonesia's agricultural sector.

The study was conducted in six provinces, West Java, Central Java, Yogyakarta, East Java, Bali, and Lampung, thereby reflecting diverse agricultural settings, varying levels of digital infrastructure penetration, and differing degrees of institutional support. Through in-depth interviews with key stakeholders, this study explores ground-level realities and facilitates comparative inter-regional analysis. This approach provides a robust empirical foundation for designing context-specific interventions and replicable AgTech adoption models. By focusing on smallholder farmers who constitute the backbone of Indonesia's

national food system, the study underscores the importance of inclusive innovation in achieving national development goals, including food security, poverty alleviation, and environmental sustainability.

Based on the established research focus, the objectives of this study are formulated as follows: 1) to identify the conditions and patterns of digital agricultural technology (AgTech) adoption among smallholder farmers across different regions of Indonesia, 2) to uncover the challenges and barriers to AgTech adoption, whether socio-economic, institutional, or technical; and 3) to evaluate the forms of governmental and institutional support that can strengthen inclusive and sustainable AgTech adoption. Employing a participatory approach and stakeholder-driven narrative analysis, the findings of this study aim to offer a robust, data-informed basis for designing contextually appropriate interventions and scalable AgTech adoption models that promote inclusive and sustainable agricultural technological innovation.

RESEARCH METHODS

Research Design

This study adopts a qualitative approach to examine in depth the dynamics of Digital Agricultural Technology (AgTech) adoption among smallholder farmers in Indonesia, with an emphasis on the importance of contextual understanding of the surrounding social, economic, and institutional conditions. This approach is deemed appropriate as it enables the exploration of actors' lived experiences and perceptions that may not be fully captured through quantitative methods, particularly within the complex agricultural sector, which is deeply intertwined with cultural norms, social relations, and local policy structures (Creswell & Poth, 2018). The research was conducted in six provinces: West Java, Central Java, Yogyakarta, East Java, Bali, and Lampung. These sites were purposively selected to represent the diversity of agricultural practices, digital infrastructure, and institutional ecosystems across different regions of Indonesia.

Data collection involved in-depth interviews and focus group discussions (FGDs). Interviews were conducted with smallholder farmers, agritech startup actors, farmer cooperatives, government agencies, agricultural extension officers, and financial service providers to capture the multiple perspectives involved in the AgTech adoption process. These interviews allowed for a deeper understanding of the motivations, concerns, and expectations of each actor. FGDs, on the other hand, were utilized to examine collective dynamics, including shared perceptions of challenges, local practices, and forms of support considered effective within each community.

Thematic analysis was employed to organize and interpret the data in accordance with the specific objectives of the study. To address the first objective, identifying the conditions and patterns of AgTech adoption across regions, the analysis focused on themes related to the forms of technology use, information dissemination channels, and the level of farmer engagement in digital innovation. For the second objective, exploring challenges and barriers to AgTech adoption, the analysis centered on narratives of structural constraints (e.g., internet access, cost, and electricity), behavioral barriers (e.g., distrust, low digital literacy), and institutional limitations (e.g., program fragmentation and misaligned regulations). To address the third objective, evaluating policy and institutional support, the analysis examined stakeholders' perceptions regarding the effectiveness of government policies, public-private partnership models, the role of extension services, and other supporting institutions in promoting inclusive and sustainable technology adoption. This approach ensures that the analysis is not only thematically robust but also directly aligned with the core focus and aims of the study.

Study Areas and Respondents

The study was carried out in six provinces in Indonesia, West Java, Central Java, Yogyakarta, East Java, Bali, and Lampung, to capture regional diversity in agricultural practices, digital infrastructure, and innovation ecosystems. These areas were strategically selected to reflect a combination of traditional farming systems, cooperative-based agriculture, AgTech innovation hubs, and government-driven agricultural programs. Each site represents a specific thematic focus within the broader context of AgTech adoption.

Fieldwork involved direct site visits and interviews at various organizations and initiatives, including greenhouse and hydroponic farms, farmer cooperatives, technology startups, smart aquaculture projects, and public institutions that support agricultural development. The primary aim of these activities was to understand how diverse actors experience and contribute to the dissemination of AgTech. The participants involved in this study represent a broad range of stakeholders within the agricultural value chain, including smallholder farmers, cooperative members, AgTech startup founders, government officials, agricultural extension officers, agribusiness actors, financial institutions, and academic experts.

Table 1. Study Sites and Research Focus

Province	Location	Research Focus
West Java	Lembang Agri, Eptilu Cooperative Garut, Bandung Agricultural Office	Greenhouse farming, cooperatives, government agricultural programs
Central Java	Sayur Organik Merbabu, Swarna Loka Semarang	Hydroponics, agricultural technology (AgTech) innovation hubs
Yogyakarta	MSMB Yogyakarta	AgTech innovation and startup development
East Java	eFishery Banyuwangi	Smart aquaculture and technology-based fisheries
Bali	Balai Benih Induk, local farming initiatives	Government-supported farming, seed development
Lampung	Community-based farming and regional AgTech initiatives	Rural agriculture, introduction of agricultural technologies

Source: Processed Primary Data

This study involved 85 respondents representing a broad spectrum of stakeholders to ensure a comprehensive understanding of the dynamics influencing the adoption of digital agricultural technologies (AgTech) in Indonesia. A purposive sampling technique was strategically employed to select informants deemed to possess relevant knowledge, experience, and direct involvement with AgTech-related issues, whether as users, providers, regulators, or facilitators. This selection aimed to capture a wide yet relevant range of perspectives that reflect the multiple dimensions embedded in the national digital agricultural innovation system. The six provinces selected as study sites were chosen due to their diverse characteristics in terms of agricultural practices, levels of digital infrastructure, and institutional configurations, thus enhancing the geographical and contextual representativeness of the data collected.

Smallholder farmers and cooperative members constituted the core of this research, as they are both the primary users and the most impacted group by the implementation of digital agricultural technologies. Their participation enabled an in-depth exploration of grassroots-level needs, challenges, and adaptation strategies. AgTech innovators and startup representatives contributed valuable insights into technology design, business models, and

commercialization barriers. Government officials and agricultural extension agents provided perspectives on policy frameworks, regulations, and public intervention schemes. Meanwhile, agribusiness actors and financial institutions expanded the analytical scope by offering viewpoints related to investment, risk management, and market integration. The involvement of academic experts enriched the conceptual framework and situated the findings within a broader scholarly context.

To ensure the validity of the findings, the study employed source triangulation by cross-checking information obtained from different categories of respondents within the AgTech system, including users, providers, and regulators alike. This triangulation process was carried out during thematic analysis by identifying consistencies and divergences in narratives across actors concerning key issues such as digital access barriers, perceptions of technological risk, and the effectiveness of government interventions. This approach is particularly relevant in a multi-sectoral and multi-level research context, as it enables cross-verification of the credibility and significance of findings from multiple viewpoints. Consequently, source triangulation strengthens the reliability of interpretation and ensures that the resulting analysis reflects the complexity and diversity of realities observed in the field.

Table 2. Research Respondents by Category

Respondent Category	Number (n)
Smallholder farmers and cooperative members	40
AgTech innovators and startup representatives	15
Government officials and agricultural extension agents	12
Agribusiness actors and financial institutions	10
Academics and researchers in digital agriculture	8
Total	85

Source: Processed Primary Data

Data Analysis

This study employed the thematic analysis framework developed by Braun & Clarke (2006) to systematically analyze data obtained from in-depth interviews and focus group discussions (FGDs). Thematic analysis was selected for its flexibility and its capacity to reveal patterns within qualitative data, making it particularly suitable for exploring the complex social, behavioral, and institutional dynamics surrounding the adoption of agricultural technology (AgTech). The analysis involved the following five key stages, as illustrated in Figure 1.

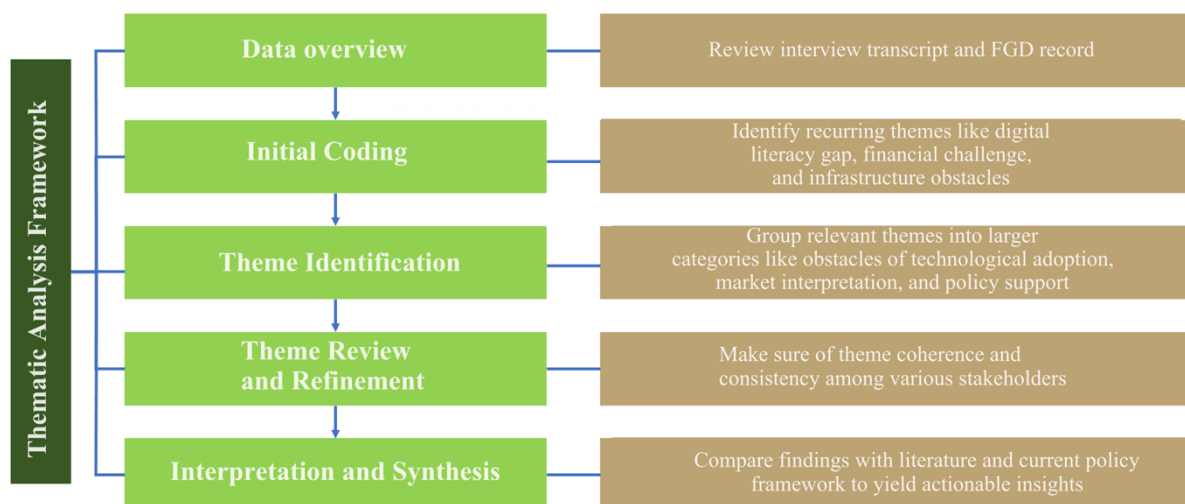


Figure 1. Thematic Analysis Framework

Source: Braun & Clarke (2006)

To complement the thematic analysis, word frequency and sentiment analyses were conducted using NVivo software. These analyses aided in identifying the most frequently mentioned keywords (e.g., “trust,” “connectivity,” “training”) and in assessing stakeholder sentiment toward AgTech. The sentiment analysis revealed general optimism regarding the potential of innovation, coupled with concern over implementation challenges.

RESULTS AND DISCUSSION

A. The Conditions and Patterns of Digital Agricultural Technology (AgTech) Adoption in Indonesia

Digital transformation in the agricultural sector is gaining momentum; however, the adoption of digital agricultural technology (AgTech) in Indonesia remains uneven. There are marked disparities between advanced cooperatives, tech-savvy agricultural entrepreneurs, and traditional smallholder farmers. Field data confirm that while some actors have progressed significantly, such as the Eptilu Cooperative in Garut and agritech enterprises like Habibie Garden and Lembang Agri, which have implemented IoT-based soil sensors, automated irrigation systems, and climate-controlled greenhouses. These innovations have not been widely or meaningfully adopted by the broader farming population.

At the Eptilu Cooperative, members reported substantial yield increases following the adoption of IoT-based irrigation systems and nutrient monitoring sensors. Similarly, Lembang Agri utilized precision irrigation integrated with microclimate control systems to enhance productivity while minimizing water waste. These successes underscore the tangible benefits of AgTech when deployed under supportive institutional and financial conditions. However, replicating these outcomes in less organized or resource-constrained farming communities remains a significant challenge.

In reality, the majority of smallholder farmers continue to rely on traditional methods and often perceive AgTech as a luxury rather than a practical solution. This perception is shaped by several factors, including high initial investment costs, unfamiliarity with digital interfaces, and uncertainties surrounding long-term reliability and maintenance. These findings align with previous research indicating that AgTech adoption is more commonly driven by commercial feasibility and institutional facilitation, via cooperatives, exporters, or agribusiness partnerships, rather than by organic demand from farmers themselves (Klerkx & Rose, 2020). This supports the broader conclusion that digital transformation in agriculture

tends to be top-down and is often hindered by inadequate contextual adaptation to the needs of small-scale users (Reichardt et al., 2009).

Sentiment analysis results highlight a perceptual divide regarding AgTech. The most positive sentiments were expressed by farmers directly involved in operating IoT-based greenhouses or smart irrigation systems, citing improved efficiency, time savings, and yield predictability as clear benefits. Neutral sentiments emerged from those who recognized AgTech's potential but remained concerned about costs, complexity, and the lack of post-installation support. Most concerning, however, was the prevalence of negative sentiment among traditional smallholder farmers, who viewed AgTech as unaffordable or unreliable, favoring manual methods passed down through generations.

One major theme emerging from the data is the persistent digital literacy gap. Although several training initiatives have been implemented, such as those facilitated by Alif Learning Center and the Self-Sustaining Agricultural and Rural Training Center (P4S) at Lembang Agri. These programs remain fragmented and lack continuity. Even agricultural extension agents themselves reported difficulties in operating new digital platforms, indicating that capacity-building efforts are needed not only for farmers but also for facilitators. This finding aligns with the study by Singh & Kapoor (2024), which argues that long-term, iterative learning processes are crucial for the effective integration of AgTech. Without consistent training that is sensitive to local contexts, even government-subsidized or distributed digital tools risk being underutilized or misused.

In several government-funded agricultural projects discussed in case studies by Rust et al. (2022) and da Silveira et al. (2023), for instance, both physical and non-physical infrastructures were provided, yet farmers were not equipped with sufficient knowledge to operate digital monitoring systems effectively. This highlights a critical insight: access does not equate to adoption. The availability of infrastructure must be accompanied by behavioral change support, technical assistance, and farmer-to-farmer learning networks to ensure sustained use. In conclusion, while innovation hubs and advanced cooperatives have demonstrated AgTech's transformative potential in the agricultural sector, broader adoption continues to be hindered by structural disparities, capacity gaps, and a deficit of trust. Bridging these divides requires an integrated strategy that combines financial accessibility, institutional coordination, and inclusive digital education tailored to the diverse agricultural contexts of Indonesia.

B. Challenges and Barriers to AgTech Adoption

Limited Access to Electricity and Stable Internet Connectivity

Across various research sites, stakeholders highlighted persistent issues with unreliable electricity and internet access, which significantly disrupt the functionality of AgTech systems. For example, the Seed Breeding Center (Balai Benih Induk, BBI) in East Java, which has integrated IoT technology for real-time monitoring in seed production, reported frequent system failures due to voltage fluctuations and unplanned power outages. A similar situation was observed at Al Ittifaq Islamic Boarding School in Bandung, which runs a community-based farming model and has experienced recurring damage to IoT devices caused by unstable electricity supply. These disruptions not only hinder productivity but also escalate the long-term maintenance costs of AgTech infrastructure, as sensitive equipment requires regular repair or replacement.

The situation is even more complex in remote agricultural areas, where internet penetration remains weak or inconsistent. Farmers participating in AgTech pilot projects in such regions expressed frustration over unstable mobile networks and low bandwidth, which rendered key features such as real-time data monitoring, automated irrigation, and remote diagnostics ineffective. Even well-resourced initiatives such as Habibie Garden and Bernard Gapoktan, which operate smart-climate greenhouses, continue to face technical interruptions due to poor network infrastructure. These findings reinforce the existing literature, which

emphasizes that digital adoption in agriculture depends not only on device availability but also on the presence of a functional supporting infrastructure ecosystem (Wolfert et al., 2017). Without reliable electricity and internet connectivity, the sustainable operation of agricultural technologies cannot be ensured. Therefore, government investment in rural electrification and digital connectivity must be aligned with AgTech implementation strategies to prevent the deepening of disparities between well-connected and marginalized regions.

Cost-Benefit Dilemma for Farmers

Beyond technical constraints, the economic feasibility of AgTech remains a critical barrier, particularly for smallholder farmers with limited financial capacity. While AgTech solutions such as IoT-based monitoring systems (e.g., CMT IoT) offer substantial long-term efficiency gains, the initial investment—estimated at approximately IDR 50 million per hectare—is perceived as prohibitively expensive for most smallholders in the absence of targeted subsidies. More advanced systems, such as greenhouse automation packages implemented in Nagrek and Ciwidey, may cost up to IDR 500 million per unit, thereby creating a pronounced gap between progressive adopters and financially constrained producers.

Government programs such as the Special Allocation Fund (DAK) have attempted to ease the financial burden through infrastructure funding. However, their implementation remains uneven. In several instances, recipients of government-funded systems lack the complementary skills and follow-up support necessary to optimize technology utilization, often resulting in suboptimal performance or complete disuse. Moreover, as evidenced by the collaboration between Bernard Gapoktan and Japan's agricultural initiatives, international partnerships can indeed help reduce costs but cannot fully address structural affordability issues without sustained institutional support.

These findings align with those of Klerkx & Rose (2020), who argue that the high initial capital requirements and uncertain return on investment are among the primary reasons smallholder farmers are reluctant to adopt digital tools. Even in contract farming models such as E-Fishery, which offer more secure market access and financial assistance, many farmers remain hesitant to commit due to commodity price volatility and concerns over the loss of autonomy. The perceived risks frequently outweigh potential benefits, particularly when technology adoption necessitates substantial behavioral and operational changes.

In conclusion, the challenges to AgTech adoption in Indonesia stem not only from technological innovation but are also deeply rooted in the material realities of rural infrastructure and the economic insecurity faced by smallholder farmers. Bridging the digital divide demands more than innovation alone. It requires coordinated infrastructure development, accessible financing mechanisms, and trust-building strategies that address the genuine concerns of the farming communities that AgTech aims to serve.

Digital Literacy and Trust in Technology

The adoption of digital agricultural technologies (AgTech) among smallholder farmers in Indonesia continues to be hindered not only by infrastructural and economic constraints but also by low levels of digital literacy and limited trust in technology, especially among older farmers and traditional farming communities. A recurring theme across research sites—including Bandung, Lampung, and Banyuwangi—is that many farmers remain skeptical about the practical benefits of digital agriculture. They view such technologies as overly complex, costly, and unreliable compared to conventional methods that have been in use for decades. This skepticism often stems from limited exposure to digital tools, prior negative experiences with underperforming technologies, or the absence of visible success stories within their social networks.

One of the key obstacles reinforcing this skepticism is the limited technical capacity of agricultural extension officers, who serve as the frontline link between government programs and farming communities. Officials at the Bandung Department of Agriculture acknowledge

that many extension workers lack adequate training in the latest AgTech developments, rendering them ill-equipped to promote digital tools or troubleshoot technical issues in the field. This is particularly problematic given earlier research findings indicating that agricultural training is pivotal for agricultural development, especially through farmers' active participation in training activities (Maulidiah et al., 2021). As a result, AgTech knowledge dissemination efforts often stall at the outreach stage, as extension agents are unable to provide practical guidance or build farmers' trust. Focus group discussions (FGDs) in Lampung and Banyuwangi further revealed that many farmers perceive AgTech as intimidating or irrelevant to the scale of their operations, reinforcing the belief that traditional methods are more dependable.

To address these challenges, several initiatives have been introduced to bridge the knowledge gap and enhance digital literacy. For example, the Balai Benih Induk (BBI) in East Java has conducted training programs aimed at equipping extension officers with a basic understanding of IoT applications in seed production, thereby enabling them to better support farmers in using sensor-based monitoring systems. In addition, Block71—a startup incubator supporting AgTech innovation—has launched mentorship programs for young farmers, aiming to foster a new generation of digitally literate agricultural entrepreneurs capable of becoming change agents in their communities.

While these efforts represent a positive first step, research findings indicate that one-off training sessions and pilot projects are insufficient to foster meaningful behavioral change. Many farmers continue to lack confidence in operating digital tools, particularly those requiring regular calibration, application use, or sensor data interpretation. This underscores the need for long-term, iterative, and context-specific capacity-building programs that go beyond information transfer to include hands-on demonstrations, peer-to-peer learning, and on-site technical assistance. As emphasized by Zscheischler, et al. (2022) and Laurent, et al. (2022), digital transformation in agriculture is not merely a technological process, but a deeply social one, requiring trust, comprehension, and sustainability.

Furthermore, trust in technology is closely tied to broader concerns about data security, maintenance costs, and perceived vulnerability to technological failure. Farmers are generally wary of tools they do not understand or cannot repair independently, particularly in areas with limited access to repair services and after-sales support. Without deliberate efforts to build trust through participatory design, transparent communication, and farmer-led innovation trials, even well-designed technologies risk being rejected or abandoned. Accordingly, digital literacy and trust are foundational prerequisites for AgTech adoption, yet both remain underdeveloped among key stakeholders in Indonesia's agricultural sector. Bridging this gap necessitates a systemic approach that prioritizes human capacity development alongside technological investment to ensure that both farmers and extension workers are equipped not only with tools but also with the knowledge and confidence to use them effectively.

Market Access and Economic Barriers

One of the most persistent barriers to the successful adoption of AgTech among smallholder farmers is not technological per se, but economic and structural, particularly concerning market access and the dominance of intermediaries. While innovations can enhance productivity and efficiency, these benefits often fail to translate into improved livelihoods when farmers remain disconnected from transparent and profitable markets. Field findings reinforce the fact that smallholders generally lack direct access to buyers and continue to depend heavily on middlemen who control prices, quality standards, and transaction terms (Abebe, Bijman, & Royer, 2016).

For instance, dragon fruit farmers in Banyuwangi have adopted smart irrigation technologies that optimize water usage and improve crop quality. Nevertheless, they continue to rely on middlemen for marketing and sales, thereby limiting the financial gains from

technological improvements. While these intermediaries provide immediate cash payments, the prices offered are significantly below market value, contributing to financial exploitation and reinforcing economic dependency.

Similarly, terrace farmers in Jatiluwih, Bali, have attempted to reduce reliance on middlemen by establishing direct partnerships with hotels to market organic rice. However, this strategy has encountered logistical challenges, including limited transportation and post-harvest infrastructure, which compromise the sustainability of direct-to-market sales. These cases highlight broader structural challenges within Indonesia's agricultural value chains, where logistics, cold storage, and market integration remain underdeveloped and ill-equipped to support smallholder participation (Janssen et al., 2017). Without supporting infrastructure, digital agriculture solutions alone are insufficient to empower farmers to access higher-value markets.

In response to these issues, several contract farming models and AgTech-based market platforms have emerged as promising alternatives. For example, the contract farming model developed by E-Fishery in the aquaculture sector has demonstrated success by providing price stability and guaranteed buyers for shrimp and fish farmers. The company offers a digital feeding system, access to financing, and integrated contracts with off-takers, significantly reducing price volatility and enhancing farmers' bargaining power.

Likewise, platforms such as Sayur Box and Nudira Fresh Greenhouse aim to connect peri-urban and rural farmers directly with urban consumers and retailers by offering premium prices for high-quality agricultural products. These platforms not only reduce dependence on intermediaries but also enhance supply chain traceability, price transparency, and planning efficiency. Nonetheless, adoption of these platforms remains limited among the majority of smallholder farmers, primarily due to barriers in digital literacy, comprehension of contractual terms, and trust in online systems. Government-led initiatives, such as Shoppertan, which seeks to integrate farmers into the e-commerce ecosystem, face similar challenges, as many farmers still prefer traditional cash-based transactions that provide immediate returns.

These findings are consistent with the study by Ezeomah (2021), which emphasizes that technology alone is insufficient to drive inclusive market integration. Digital agriculture platforms must be embedded within a broader ecosystem that encompasses financial literacy, last-mile logistics, institutional coordination, and trust-building efforts. For instance, although digital contracts may offer more secure income streams, farmers unfamiliar with legal frameworks or digital platforms may feel intimidated or face access difficulties, which ultimately exacerbates existing inequalities.

In the end, overcoming market access barriers and economic constraints requires an integrated strategy that combines digital innovation with the strengthening of local capacities, infrastructure support, and inclusive financing mechanisms. Only when smallholder farmers are equipped not only with tools but also with the knowledge, access, and capacity to actively participate in formal markets, can AgTech become a transformative force for rural livelihoods and the sustainability of the agricultural sector in Indonesia.

C. Government Policy and Institutional Support for AgTech Adoption ***The Gap Between Infrastructure Investment and Training***

Various government-led initiatives, such as the Special Allocation Fund (DAK) and greenhouse subsidies provided by the Ministry of Agriculture, have played a significant role in expanding AgTech infrastructure. However, there remains a substantial gap between the provision of technology and the development of human resource capacity. In several documented cases during fieldwork, farmers received greenhouses equipped with advanced IoT-based monitoring systems but lacked the basic training necessary to operate or interpret the data generated by such devices. As a result, these systems were underutilized or misused, failing to deliver the anticipated productivity gains.

This implementation gap is not limited to farmers. Agricultural extension workers, who play a central role in disseminating agricultural knowledge, also reported in focus group discussions (FGDs) that they often feel unprepared and cannot guide farmers through the digital transition. Many of them still have limited exposure to AgTech and continue to rely on outdated training materials that no longer reflect current developments in precision agriculture, IoT, or data-driven farming practices.

These findings highlight a systemic mismatch between investments in hardware and the provision of soft infrastructure, namely knowledge and skills. This is in line with the argument of Gardezi, et al. (2022), who contend that top-down digitalization efforts tend to fail when they overlook local contexts and fail to meaningfully engage users in the adoption process. AgTech policies that prioritize infrastructure development must be accompanied by capacity-building programs that are local, participatory, and sustainable, so that the availability of digital tools is matched by effective usage. Without this alignment, government programs risk reinforcing a cycle of technological stagnation, where devices are available but remain unimplemented due to low digital literacy and weak institutional responsiveness.

Public-Private Partnerships (PPPs) as a Potential Solution

In contrast to the various limitations discussed above, several examples from the field suggest that public-private partnerships (PPPs) can serve as an effective mechanism for addressing both infrastructure gaps and capacity constraints. For example, a collaboration between the Ministry of Agriculture, the Japan International Cooperation Agency (JICA), and Bernard Gapoktan in West Java introduced the IoT-based Pot-Up system. What distinguished this initiative was not only the deployment of smart technologies but also the provision of direct training, co-designed training modules, and adaptive support that enhanced farmers' confidence and crop resilience.

Similarly, the partnership between E-Fishery and government agencies demonstrates how PPPs can be leveraged to provide structured financing, regulatory alignment, and extension support. Through integrated services—including digital feeding systems, app-based monitoring, access to working capital, and technical assistance—E-Fishery has built an ecosystem in which AgTech adoption becomes not only feasible but also appealing to aquaculture actors. These cases reflect a broader argument advanced by Agarwal, Malhotra, & Dagar (2023), who assert that effective PPPs can overcome state capacity limitations by combining private-sector innovation with public-sector reach.

What makes PPPs promising as a solution is their potential to scale inclusive AgTech adoption, particularly in rural and underserved areas. However, their effectiveness depends on the alignment of incentives, clear governance structures, and accountability mechanisms to prevent elite capture or top-down policy imposition. PPPs must also be supported by regulatory reforms, such as data governance policies, subsidy mechanisms for smallholder adoption, and protective frameworks for digital contracts.

In conclusion, although the Indonesian government has taken significant steps to expand AgTech infrastructure, the effectiveness of these investments will largely depend on the ability to bridge the gap between technological deployment and user readiness. This can be achieved through a more participatory policy framework and the strategic strengthening of PPP models that prioritize both innovation and inclusivity. Aligning institutional support with on-the-ground realities will be key to driving a sustainable and equitable digital transformation of Indonesia's agricultural sector.

CONCLUSION

This study finds that the conditions and patterns of digital agricultural technology (AgTech) adoption in Indonesia remain highly varied across regions, with uneven distribution and generally limited uptake among smallholder farmers. While there has been increased adoption through certain local initiatives and pilot projects, the majority of farmers continue

to face a range of interrelated structural barriers. Inadequate digital infrastructure—especially in rural and remote areas—combined with limited access to stable electricity and internet connectivity, serves as a major constraint to the widespread utilization of digital technologies. Financial limitations and restricted access to affordable financing schemes further hinder smallholder farmers' ability to acquire and implement such technologies.

From a social and institutional standpoint, the study identifies low levels of digital literacy, insufficient extension capacity, and the dominance of middlemen in agricultural supply chains as key challenges that undermine AgTech's potential to improve farmer welfare. Although digital platforms offer the promise of price transparency and broader market access, many farmers still face gaps in digital skills, trust in new systems, and access to supporting logistics. These factors suggest that AgTech-related challenges are not merely technical but also involve complex social and institutional dimensions that require holistic solutions.

About policy and institutional support, the study indicates that public-private partnerships (PPPs) represent a promising approach to scaling AgTech adoption, especially when designed to be inclusive and responsive to local needs. However, one-off interventions have proven insufficient. Long-term strategies are required, combining human capacity development, expansion of digital infrastructure, fiscal incentives for AgTech innovators, and adaptive extension services. Therefore, contextualized and sustainable policies are essential to foster an AgTech ecosystem capable of driving inclusive digital agricultural transformation and meaningfully empowering smallholder farmers.

RECOMMENDATIONS

Based on the findings of this study, several strategic recommendations are proposed to guide future efforts in enhancing the adoption of digital agricultural technologies (AgTech) among smallholder farmers in Indonesia. First, it is critical to recognize that low digital literacy, among both farmers and agricultural extension workers, is a major barrier to effective technology adoption. Policymakers and development practitioners must prioritize the development of structured and sustainable digital literacy programs that not only introduce AgTech concepts but also build confidence and long-term skills for their use. These programs should be contextual, participatory, and integrated with local institutions to ensure relevance and accessibility.

Second, it is essential to align infrastructure investments with capacity-building efforts. The provision of IoT-enabled greenhouses or digital tools without adequate training leads to suboptimal use and inefficiency. Future government initiatives should adopt an integrated approach wherein the deployment of technology is accompanied by long-term mentoring, technical support, and community engagement.

Third, addressing the financial constraints faced by smallholder farmers is an urgent priority. Innovative financing models, such as blended finance, micro-leasing schemes, outcome-based subsidies, or cooperative loans, should be developed to reduce initial costs and perceived risks. Further research is recommended to explore inclusive financing mechanisms that can be tailored to different farm scales, commodity types, and regional economic conditions.

Fourth, the study highlights the potential of public-private partnerships (PPPs) as a scalable solution. However, existing PPP models need to be refined and expanded to underserved regions. Future research should examine PPP governance frameworks that emphasize transparency, shared accountability, and measurable impacts in digital agriculture initiatives. Comparative evaluations of PPP models across commodities and geographic regions would be highly valuable in shaping more strategic and effective policies.

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