OPEN ACCESS

Journal of Agribusiness and Natural Resources | Vol. 1 No. 3 (2025)

Research Article

Digital Technology Adoption by Smallholder Farmers in Indonesia

Muhammad Hasyim
Horticultural Crop Production Technology Study Program, Politeknik Murakata, Indonesia
Email: mhasyim844@gmail.com

Received:	Revised:	Accepted:	Online:
December 16, 2025	January 14, 2026	January 22, 2026	January 29, 2026

Abstract
Digital transformation in the agricultural sector offers significant opportunities to enhance the productivity, efficiency, and welfare of smallholder farmers in Indonesia. Nevertheless, the rate of digital technology adoption among smallholder farmers remains relatively low due to limited digital literacy, infrastructure access, economic risks, and suboptimal institutional support. This study aims to develop a more comprehensive conceptual framework to explain the dynamics of digital technology adoption by smallholder farmers in Indonesia. The research employs a qualitative approach with a conceptual paper design through a systematic conceptual review of relevant international and national literature, alongside a synthesis of key theories including Diffusion of Innovation (DOI), Technology Acceptance Model (TAM), and Unified Theory of Acceptance and Use of Technology (UTAUT). The analytical findings indicate that digital technology adoption is a multidimensional socio-technical process involving the interaction of individual cognitive capacity, household economic stability, community social capital, digital infrastructure readiness, and policy and institutional support. Based on theoretical integration and cross-country empirical findings from developing nations, this study develops the Adaptive Socio-Technical Agrarian Digitalization (ASTAD) model, which emphasizes a dynamic adaptive process within the agrarian ecosystem. This model extends classical approaches by incorporating variables such as economic risk buffer capacity, digital learning elasticity, collective trust, digital access stability, and market integration. The contribution of this research lies in reinforcing a systemic perspective for understanding smallholder agricultural digitalization in Indonesia, along with policy implications for promoting an inclusive and sustainable digital ecosystem.

Keywords: Agricultural Digitalization, Digital Technology Adoption, DOI, TAM, UTAUT

1. Introduction

Agriculture by smallholder farmers plays a central role in food security, poverty reduction, and economic stability in many developing countries such as Indonesia. Small-scale farmers contribute a significant proportion of agricultural production yet continue to face substantial structural challenges, including limited access to technology, capital, and accurate agronomic information which are factors that contribute to low productivity and constrained farm scale. The adoption of digital technology in the agricultural sector has the potential to deliver timely market information, improve decision-making, and optimize agricultural inputs, thereby enhancing farmer welfare (digital agriculture ecosystems) (Gumbi et al., 2023).

Agricultural digitalization encompasses the use of information and communication technology (ICT), mobile phone-based applications, IoT sensors, and digital platforms that offer agricultural services such as weather information, market prices, and product marketing. However, the adoption of such digital solutions among smallholder farmers remains limited, primarily due to barriers such as uneven digital infrastructure and a lack of technological literacy. Agricultural digital ecosystems for smallholder farmers in many regions remain "underdeveloped," which impacts the low widespread utilization of digital technology (Arangurí et al., 2025).

Other challenges identified in the literature include low levels of digital literacy among farmers, limited technical skills, and cost barriers to technology use. In this regard, digital skills constitute one of the primary determinants of successful technology adoption, as the ability to understand and utilize digital tools greatly influences the extent to which technology can enhance productivity and market access (Choruma, 2024).

In the context of Sub-Saharan Africa and other developing countries, it has also been found that barriers to technology adoption by smallholder farmers include limited internet connectivity, lack of institutional support, gender issues, and disparities in access to technology services between urban and rural locations (Arangurí et al., 2025). Nevertheless, the potential benefits of digitalization such as improved market access, data-driven decision-making, and increased income indicate significant opportunities for smallholder farmer empowerment if these barriers can be overcome.

In Indonesia, research by Sasmita (2026); Satria et al. (2025); and Sihombing & Hubeis (2024) indicates that despite various digital initiatives in the agricultural sector, the rate of digital technology adoption among smallholder farmers remains low. This is characterized by the tendency of most farmers to use basic technology such as simple mobile phones, while not yet widely utilizing more sophisticated agricultural applications for production optimization and marketing. Determinant factors such as motivation, digital skills, educational level, and access to ICT experience have been proven to significantly influence digital technology adoption among young farmers in certain regions of Indonesia.

Digital technology adoption in the agricultural sector is not only influenced by the individual characteristics of farmers, but also by social structural factors, public policy, institutional support, and access to technological resources (Nxumalo & Chauke, 2025). The facilitation of training, supportive policies, and multi-stakeholder collaboration in providing technology access are important for increasing the likelihood of sustainable technology adoption by smallholder farmers.

Although a number of studies have raised the determinants of technology adoption in developing countries, there remain conceptual gaps to be filled regarding a holistic understanding of how digital ecosystems can be accessed, understood, and effectively utilized by smallholder farmers in Indonesia. This theoretical void provides a strong rationale for composing a conceptual study that integrates international findings with the local Indonesian context. This research is expected to offer a new conceptual model that is more suitable for explaining the dynamics of digital technology adoption among smallholder farmer groups, while also providing policy inputs to strengthen agricultural digitalization strategies in Indonesia.

2. Literature Review

2.1. The Concept of Technology Adoption in Agriculture

Agricultural technology adoption is a process by which farmers accept, apply, and utilize technological innovations in their farming practices to enhance productivity and welfare. Conceptually, technology adoption involves not only the technology itself, but also farmer behavior, technology characteristics, and the broader social and institutional context. Technology adoption literature indicates that this process is influenced by innovation attributes, household characteristics, socio-economic factors, and institutional support which are factors commonly referenced in diffusion of innovation theory and technology behavior models such as TAM (Technology Acceptance Model) and UTAUT (Unified Theory of Acceptance and Use of Technology) (Fardani et al., 2024).

Agricultural digitalization refers to the integration of digital technologies such as smartphone-based applications, market information systems, the Internet of Things (IoT), big data, and e-commerce

platforms into the production, distribution, and marketing processes of agricultural products. This transformation is often associated with the concept of Agriculture 4.0, which emphasizes data-driven efficiency and precision decision-making (Klerkx et al., 2019).

2.2. Theories and Models of Technology Adoption

Theories and models of technology adoption have evolved significantly in explaining how individuals and groups accept and use new innovations. One of the most widely used classical frameworks is the Diffusion of Innovation (DOI) proposed by Orr (2003). This theory emphasizes that the adoption process is influenced by innovation attributes, namely relative advantage, compatibility, complexity, trialability, and observability. Additionally, DOI places the social system as an important factor in accelerating or slowing the diffusion of innovation. In the context of agriculture, digital technology perceived as relevant to local practices, easy to understand, and offering clear economic benefits tends to be adopted more quickly by farmers. Conversely, innovations that are complex and inconsistent with the socio-economic conditions of smallholder farmers are likely to face resistance or slow adoption.

With the development of information technology, the behavioral approach to technology adoption was further strengthened through the Technology Acceptance Model (TAM) developed by Davis (1989b). This model emphasizes that an individual's decision to use technology is determined by two core constructs: perceived usefulness (PU) and perceived ease of use (PEU). PU refers to the degree to which an individual believes that using technology will improve their performance or productivity, while PEU relates to the perception of how easy the technology is to use.

In the context of smallholder farmers, if digital agricultural applications are perceived as capable of improving crop yields, expanding market access, or facilitating access to price and weather information, and do not require complex technical skills, then the likelihood of adoption increases. However, TAM has often been criticized for focusing too heavily on individual cognitive aspects while giving insufficient consideration to structural factors such as infrastructure access and institutional support. To address these limitations, Venkatesh et al. (2003) developed the Unified Theory of Acceptance and Use of Technology (UTAUT), which integrates various earlier adoption theories into one comprehensive model. UTAUT adds variables such as performance expectancy, effort expectancy, social influence, and facilitating conditions as primary determinants of behavioral intention and technology use behavior. The model also considers the moderating role of demographic factors such as age, gender, and experience. In the context of digital agriculture, the availability of supporting facilities such as internet access, training, extension services, and encouragement from farmer groups or the government becomes an important factor influencing actual adoption. Therefore, UTAUT is considered more capable of explaining the dynamics of digital technology adoption among smallholder farmers, as it accommodates both individual dimensions and the broader social and institutional context.

2.3. Determinant Factors of Agricultural Technology Adoption

The adoption of agricultural technology by smallholder farmers is not singular in nature, but rather is influenced by a combination of individual, structural, and institutional factors that interact with one another. Research in developing countries consistently affirms that low adoption rates are not solely caused by resistance to innovation, but also by limited capacity, access, and systemic support (Martha et al., 2012). Conceptually, the determinants of agricultural technology adoption can be grouped into the following dimensions:

a) Individual and Household Factors

At the micro level, farmer characteristics are the primary determinants in the innovation acceptance process. Educational level, age, farming experience, and digital literacy influence a farmer's

capacity to understand the benefits and risks of new technology. Feder et al. (1985) showed that farmers with higher levels of education tend to have a greater probability of adoption because they possess better analytical capacity and information access. Low digital literacy in rural areas is also frequently a significant barrier to the use of internet-based applications and digital information systems (Trendov et al., 2019).

b) Infrastructure and Technology Access

Structural dimensions such as electricity availability, telecommunications networks, and internet connectivity constitute the basic prerequisites of agricultural digitalization. Without adequate infrastructure, digital technology cannot be optimally implemented, even if farmers express interest. Infrastructure gaps in rural areas widen the digital divide and restrict the utilization of modern agricultural innovations (Clapp & Ruder, 2020). Furthermore, the cost of devices and internet access also constitutes a significant barrier for smallholder farmers with limited capital (Rotz et al., 2019).

c) Institutional and Social Support

Beyond individual and infrastructure factors, institutional support plays a strategic role in accelerating innovation diffusion. The role of agricultural extension workers, farmer groups, social networks, and government policies has been proven to increase farmers' trust and intention to adopt new technologies. The Unified Theory of Acceptance and Use of Technology (UTAUT) emphasizes the importance of facilitating conditions and social influence in determining actual technology use (Venkatesh et al., 2003). In the context of digital agriculture, technical training, technology subsidies, and public-private partnerships constitute important instruments for building an inclusive innovation ecosystem (Klerkx et al., 2019).

3. Methods

This study employs a qualitative approach with a conceptual paper design aimed at developing a conceptual framework regarding digital technology adoption by smallholder farmers in Indonesia. This approach does not focus on testing empirical hypotheses, but rather on theoretical synthesis and critical analysis of relevant literature in order to construct a more comprehensive conceptual model.

The method used is a systematic conceptual review, which is a structured process of identifying, selecting, and synthesizing scientific literature to examine theories, models, and empirical findings related to digital agricultural technology adoption. Research data sources consist of secondary literature obtained from internationally reputable academic databases such as Scopus, Web of Science, ScienceDirect, SpringerLink, Taylor & Francis, and Google Scholar for supporting literature, as well as nationally relevant publications pertaining to the Indonesian context.

Analysis was conducted through a narrative and comparative synthesis approach applied to key theories, including Diffusion of Innovation (DOI), Technology Acceptance Model (TAM), and Unified Theory of Acceptance and Use of Technology (UTAUT). Subsequently, an integration of individual, structural, and institutional dimensions was performed to construct a more contextually relevant conceptual framework for smallholder farmers in Indonesia. This process involved conceptual data reduction, categorization of determinant factors, and the formulation of theoretical propositions as the basis for conceptual model development.

Conceptual validity in this study was maintained through triangulation of literature sources and the use of references from internationally reputable journals. Through this approach, the research is expected to make a theoretical contribution by strengthening and integrating a technology adoption model that is more suitable to the socio-economic characteristics of smallholder farmers in Indonesia, while also providing policy implications for the development of inclusive agricultural digitalization.

4. Results and Discussion

4.1. Patterns of Determinants of Digital Technology Adoption among Smallholder Farmers

Digital transformation in the agricultural sector cannot be reduced solely to a matter of technology device availability or internet penetration in rural areas. Current literature consistently demonstrates that digital technology adoption among smallholder farmers is a complex socio-technical process, in which technology use decisions are shaped by the simultaneous interaction between individual capacity, social structure, household economic conditions, infrastructure readiness, and institutional and public policy configurations. Accordingly, the patterns of adoption determinants are not linear or singular, but rather multidimensional, contextual, and highly dependent on the agrarian ecosystem into which the technology is introduced.

Conceptually, the Diffusion of Innovation framework explains that innovation adoption is influenced by attributes such as relative advantage, compatibility, and complexity. However, in the context of smallholder farmers in developing countries, these attributes do not carry a uniform objective meaning. The perception of relative technology benefit is highly dependent on cognitive capacity, digital experience, and the level of ICT literacy of the user. Alant (2021) demonstrated that the ICT literacy level of smallholder farmers bears a significant relationship with age and educational level in the use of digital weather forecasting systems. This finding indicates that relative advantage is not merely an inherent characteristic of the technology, but rather the product of the user's socio-cognitive construction. A technically superior technology will not be perceived as beneficial if users lack the capacity to understand, interpret, and integrate it into their daily production practices. This aligns with the findings of Klerkx et al. (2019) which affirm that agricultural digitalization is only effective when it aligns with the practical needs of farmers and does not exceed their adaptive capacity. Thus, DOI in the agricultural context requires conceptual extension to include user capacity as a mediating variable between innovation attributes and adoption decisions.

The Technology Acceptance Model approach, which emphasizes perceived usefulness and perceived ease of use, also receives empirical confirmation, but in the agricultural sector these two constructs carry a more complex economic dimension. For smallholder farmers, the perception of usefulness is not merely related to technical efficiency, but also to the technology's ability to reduce production risk and maintain income stability. Gizachew (2024) found that the adoption of digital tools by ginger producers in Ethiopia was not only influenced by education and digital experience, but also had a significant impact on household welfare. This means that technology adoption becomes part of the household's economic strategy in facing commodity price uncertainty and climate change. However, the relatively high level of risk aversion in low-income groups causes technology investment decisions to be made very cautiously. The perception of usefulness will increase when economic benefits can be observed in a concrete and relatively short timeframe. Accordingly, in the context of small-scale farming, TAM needs to be extended by incorporating economic risk and income security variables as primary determinants of benefit perception formation.

The UTAUT model, which adds the dimensions of social influence and facilitating conditions, further clarifies that technology adoption is not merely an individual rational decision, but rather the result of social interaction and structural enabling conditions. In agrarian societies, social influence is collective in nature and grounded in interpersonal trust. Omulo (2020) showed that farmer-to-farmer digital networks through the Wefarm platform in Kenya were able to improve agricultural performance through horizontal information exchange, reinforcing innovation legitimacy at the community level. This finding illustrates that technology adoption receives validation through the experiences of fellow

farmers, not only through institutional promotion. Silvestri (2021) also demonstrated that the integration of radio and SMS in Tanzania significantly increased smallholder farmer participation in sustainable agricultural practices. This fact affirms that simple technologies integrated with local communication systems are often more effective than complex digital applications that are incompatible with rural social ecosystems.

The dimension of facilitating conditions within the UTAUT framework has been proven to play an important role in the process of digital technology adoption in the agricultural sector. Research by Kitole (2024) shows that digital transformation in Tanzania can only proceed effectively when supported by stable internet access, adequate microfinancing mechanisms, and the integration of digital platforms with local and national market chains. When these three elements are not sufficiently available, digitalization initiatives tend to be partial and have limited impact on smallholder farmer productivity. Consistently, Mushi (2022) highlights that the primary structural barriers in agricultural digitalization include limited telecommunications infrastructure, high costs of digital devices, and low interoperability between digital service platforms. Accordingly, structural factors are not merely supporting elements, but constitute essential prerequisites for the occurrence of sustainable technology adoption. Without adequate infrastructure readiness and effective financing mechanisms, individual farmer capacity and community social motivation will be insufficient to drive substantial digital transformation in agricultural practices.

Furthermore, the institutional dimension demonstrates that agricultural digitalization develops within a multi-actor ecosystem involving government, the private sector, financial institutions, and civil society organizations. Marikyan et al. (2023) showed that clear policy and regulatory support accelerate technology adoption in traditional sectors. In the agricultural context, Ding (2022) proved that the combination of digital services and human assistance significantly reduced the use of nitrogen fertilizer in China, demonstrating the effectiveness of a hybrid service model. Oyinbo (2020) also emphasized the importance of involving extension workers in the design of digital extension tools so that technology truly aligns with field-level needs. Meanwhile, Singh (2022) demonstrated that the utilization of ICT-based data enables more targeted and precise assistance in the agricultural adoption process. This affirms that institutional determinants encompass the system's capacity to perform user segmentation and personalize data-driven services. Based on these perspectives, the conceptual framework of agricultural technology adoption is illustrated in Figure 1.

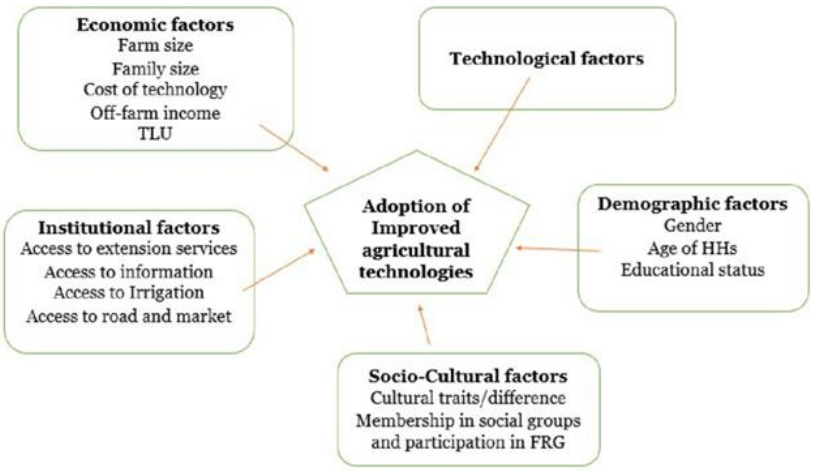

Figure 1. Conceptual Framework of Agricultural Technology Adoption

Overall, the integration of theory and cross-country empirical evidence from developing nations demonstrates that the patterns of digital technology adoption determinants among smallholder farmers form a systemic configuration consisting of individual cognitive capacity, community social capital, household economic stability, infrastructure readiness, and policy- and data-based institutional support. These five dimensions do not operate in isolation, but rather mutually reinforce or weaken one another. Disparity in one dimension can impede the entire digital transformation process. Therefore, agricultural digitalization must be understood as a reconstruction of the agrarian system based on technology and institutions, not merely as digital application penetration. Without a systemic and integrative approach, technology adoption risks being partial, unsustainable, and even widening the inequality gap among smallholder farmers.

4.2. Theoretical Model Integration of DOI, TAM, and UTAUT in the Agricultural Context

Digital technology adoption in small-scale agriculture in Indonesia is a multidimensional phenomenon involving the interaction of individual, social, cultural, economic, and technical factors. Although many studies use a single model to explain technology adoption, a singular approach frequently fails to capture the complexity of the dynamics that occur in the field. Smallholder farmers face barriers in the form of limited digital literacy, capital, information networks, and cultural resistance to modern innovation. This demands the development of a more comprehensive conceptual framework by integrating relevant theories such as DOI, TAM, and UTAUT. This integration aims not only to explain the determinants of adoption, but also to identify contradictions between theory and practice, and to provide a basis for adaptive policy interventions.

4.2.1. Diffusion of Innovation (DOI)

Diffusion of Innovation (DOI) emphasizes the process of spreading innovation within communities through adoption by individuals and social groups. Innovation attributes influencing adoption include relative advantage, compatibility, complexity, trialability, and observability. In the agricultural context, DOI helps understand the extent to which farmers assess the relative advantage of digital technology, its compatibility with traditional practices, and the ease of observing the benefits of innovation. The DOI model offers a strong perspective on how innovations spread in society through adoption by individuals and social groups. Innovation attributes such as relative advantage, compatibility, complexity, trialability, and observability can explain why certain farmers quickly adopt new technologies while others are slow or resistant.

Although DOI is effective in explaining the spread of innovation and the influence of social networks, the model is macro and descriptive in nature, and therefore does not adequately reveal the psychological motivations of individuals or the internal dynamics of farmer groups. Furthermore, DOI overlooks the actual contextual barriers experienced by smallholder farmers, such as infrastructure limitations, technology costs, or restricted internet access. DOI also fails to explain the phenomenon of cultural resistance and skepticism toward new technology, which often constitutes a critical factor in adoption failure within farming communities. Accordingly, while DOI provides important insights regarding innovation diffusion, the model is unable to explain why individuals choose to delay, reject, or modify technology use in accordance with local conditions.

4.2.2. TAM Technology Acceptance Model

TAM emphasizes individual perceptions of perceived usefulness (PU) and perceived ease of use (PEOU) as the primary determinants of behavioral intention and technology use behavior. This model is relevant for assessing farmer attitudes toward digital applications or smart farming systems. The

Technology Acceptance Model (TAM) emphasizes individual perceptions of perceived usefulness (PU) and perceived ease of use (PEOU) as the primary determinants of behavioral intention and technology use behavior. In the agricultural context, TAM can help explain farmer attitudes toward digital applications or smart farming systems.

However, TAM focuses too heavily on individual psychological factors, thereby overlooking significant social, cultural, and external structural influences. For instance, peer influence, farmer group support, government policies, and technology subsidies may be stronger determinants than individual perception alone. Additionally, TAM is linear in nature and insufficiently flexible to explain the iterative and adaptive process of technology adoption, in which practical experience, benefit observation, and repeated community interactions can alter farmer attitudes and behavior. Accordingly, TAM provides a partial understanding and needs to be integrated with other models to capture the social context and innovation more comprehensively.

4.2.3. UTAUT Unified Theory of Acceptance and Use of Technology

UTAUT integrates several previous models including TAM and the Theory of Reasoned Action, and adds key constructs of performance expectancy, effort expectancy, social influence, facilitating conditions, and moderating variables such as age, gender, experience, and voluntariness. This model offers a more holistic framework encompassing individual, social, and contextual factors. UTAUT offers a more holistic framework by taking into account the constructs of performance expectancy, effort expectancy, social influence, facilitating conditions, and demographic moderation such as age, gender, experience, and voluntariness. This model is highly useful for assessing technology adoption because it combines individual, social, and contextual factors.

However, UTAUT has been most extensively tested in formal organizational settings, and therefore requires significant adaptation for application to smallholder farmers, who have informal networks, varying technological capacity, and diverse digital experience. Although UTAUT captures social influence and facilitating conditions, the model insufficiently emphasizes specific agricultural innovation attributes such as trialability and observability, which are important for evaluating technology benefits prior to implementation. The complexity of the model also presents challenges in operationalizing indicators, potentially introducing interpretive bias if applied without local adaptation. Accordingly, while UTAUT promises a holistic framework, it remains insufficient to fully explain the process by which attitudes are transformed into actual behavior within smallholder farming communities.

4.3. Conceptual Model of Digital Technology Adoption Dynamics among Smallholder Farmer Groups

In the context of agricultural digitalization, the aspect of adaptation describes the process of behavioral and capacity change among farmers in relation to continuously evolving technology amid social, economic, and infrastructural challenges within the agrarian environment. Empirical research indicates that agricultural technology adoption is influenced by the complex interaction between farmer characteristics, socio-economic conditions, and structural barriers such as digital infrastructure access and technological literacy, such that technology adoption does not occur automatically, but rather through a dynamic adjustment process (adaptive process) in order to achieve the benefits of use (usefulness) in actual practice. Satria et al. (2025) found that the implementation of digital technology among smallholder farmers is still constrained by barriers such as low digital literacy, uneven infrastructure access, and the need for contextual training and support, demonstrating that farmers are adaptive to technology when there is synergy between individual capacity, social support, and external conditions that facilitate adoption. These results are consistent with the findings of Xu et al. (2026)

which emphasize that farmers' adaptive capacity toward digital technology is influenced not only by internal factors such as learning ability and risk readiness, but also by external factors such as institutional support and adequate ICT infrastructure, which work simultaneously to enable a continuous adaptation process within a rapidly changing agricultural ecosystem. Based on this perspective, the Adaptive Socio-Technical Agrarian Digitalization Model (ASTAD) is proposed as illustrated in Figure 2.

Figure 2. Adaptive Socio-Technical Agrarian Digitalization Model (ASTAD)

The ASTAD (Adaptive Socio-Technical Agrarian Digitalization) model was developed in response to the limitations of classical technology adoption models such as DOI, TAM, and UTAUT in the context of smallholder agriculture in Indonesia. While DOI emphasizes innovation attributes such as relative advantage and trialability, and TAM emphasizes individual perceptions of usefulness and ease of use, and UTAUT adds social influence and facilitating conditions, none of these three models adequately captures the complexity of technology adaptation in an agrarian ecosystem influenced by economic risk, uneven infrastructure, and the collective dynamics of farmer groups (Montes de Oca Munguia et al., 2021; Sihombing et al., 2024; Tumiwa & Tuegeh, 2025).

In ASTAD, variables such as Economic Risk Buffer Capacity (ERBC) and Digital Learning Elasticity (DLE) capture the individual adaptive capacity to face risk and learn from experience, while Collective Trust Infrastructure (CTI) and Peer Demonstration Effect (PDE) emphasize the socio-collective dynamics within farmer groups. Infrastructure and policy are reinforced through Digital Access Stability (DAS), Platform Usability Fit (PUF), Policy Coherence Index (PCI), and Hybrid Advisory Strength (HAS), which enable farmers to adopt technology sustainably even in the face of limited access and bureaucratic intervention. At the market layer, variables such as Market Integration Leverage (MIL) and Incentive Visibility Factor (IVF) ensure that technology adoption is directly linked to concrete and rapidly visible economic benefits, thereby reinforcing the overall adaptation process (Rusliyadi et al., 2023; Xu et al., 2026).

Through this multi-layer integration, ASTAD is able to bridge the gaps present in classical models namely, insufficient attention to farmer economic risk, digital market access, systemic policy intervention, and the smallholder/collective context, making it a more relevant model for agricultural digitalization in Indonesia. The model emphasizes that technology adoption is not merely an individual

decision, but rather a dynamic adaptive process involving the interaction of individual, social, infrastructure, institutional, and market factors, reinforced through a circular reinforcement system to ensure the sustainability of adoption and economic benefits.

4.4. Integrative DOI-TAM-UTAUT Approach in the Analysis of Digital Farming Adoption

The use of any single theoretical model whether Diffusion of Innovation (DOI), Technology Acceptance Model (TAM), or Unified Theory of Acceptance and Use of Technology (UTAUT) is frequently insufficient to explain the complexity of digital technology adoption dynamics among smallholder farmers in Indonesia. This complexity arises because technology adoption decisions in the agricultural sector are not merely the result of individual rational deliberation, but are also influenced by the social structure of the community, household economic capacity, the availability of digital infrastructure, and the institutional support that surrounds it. Sihombing & Hubeis (2024) demonstrated that the variables of performance expectancy, effort expectancy, and facilitating conditions significantly influence the intention and behavior of smallholder farmers in using digital agricultural applications. These findings reveal that the expectation of performance improvement and ease of use, as well as the availability of facility support such as internet access and training, constitute important determinants in the adoption process. However, that research focused primarily on the UTAUT framework without integrating innovation attributes such as relative advantage or trialability as emphasized in DOI, nor did it include in-depth exploration of the formation of usefulness and ease of use perceptions as formulated in TAM. These limitations indicate that while UTAUT is capable of explaining the relationship between performance expectancy and structural support toward use intention, the model does not adequately address how technology characteristics and farmers' initial experiences shape the decision-making process in a gradual and dynamic manner.

Within the DOI framework introduced by Everett Rogers through Diffusion of Innovations, innovation adoption is influenced by attributes such as relative advantage, compatibility, complexity, trialability, and observability. This perspective is highly relevant in the context of smallholder farming, where adoption decisions are often not made in a purely individual manner, but rather through a process of social observation and learning within the community. Smallholder farmers tend to first observe the success of fellow farmers before deciding to adopt a particular technology. The attributes of observability and trialability become crucial because digital agricultural technologies such as weather prediction applications, online marketing platforms, or production record-keeping systems require concrete, directly observable proof of benefit in everyday practice. Research by Abdulai et al. (2023) showed that limited access to digital infrastructure and technological literacy directly influences the perception of technology benefit, thereby impeding the diffusion process at the community level. These findings illustrate that innovation attributes cannot be separated from the structural conditions that surround them. In other words, a technology may possess relative advantage in a technical sense, but will not be perceived as superior if it is incompatible with farmers' socio-economic conditions or too complex to operate within the constraints of limited digital literacy. Therefore, the integration of DOI becomes important for explaining adoption variation across regions and farmer groups, which cannot be fully explained by the behavioral intention variables in UTAUT.

On the other hand, TAM, developed by Fred D. Davis, emphasizes that perceived usefulness and perceived ease of use are the primary determinants of technology acceptance (Davis, 1989a). The adoption of e-commerce by agro-entrepreneurs shows that the perception of usefulness and ease of use significantly influences attitudes and intentions toward using digital platforms (Nagy et al., 2025). These findings indicate that before social or institutional factors come into play, the individual cognitive

process plays a fundamental role in shaping attitudes toward technology. However, TAM tends to focus on the individual psychological dimension and gives insufficient consideration to collective social influence and rural infrastructure limitations. In practice, smallholder farmers do not always have complete freedom to make decisions based on personal perception, as such decisions are frequently influenced by farmer group norms, extension worker recommendations, or household economic pressures. Therefore, without integration with DOI and UTAUT, TAM risks oversimplifying the reality of adoption, which in practice is influenced by social relations, network access, and institutional support.

When all three models are considered simultaneously, it becomes apparent that each has a different but complementary analytical focus. DOI explains how innovations spread within social systems and how technology attributes influence the initial adoption decision. TAM deepens the analysis at the level of individual perception, specifically how farmers assess the usefulness and ease of use of technology. Meanwhile, UTAUT integrates social factors and facilitating conditions to explain how such intentions are translated into actual use behavior. In the context of smallholder farmers in Indonesia, who frequently face capital limitations, low digital literacy, and infrastructure inequality, the integration of all three theories becomes increasingly relevant. The process of digital technology adoption does not occur linearly, but rather proceeds through stages of awareness, evaluation, trial, initial use, and sustainable adoption. These stages involve the interaction of perceived benefit, direct experience, social influence, and structural support.

The integration of DOI, TAM, and UTAUT enables a more comprehensive explanation of the phenomenon of resistance or failure of digital technology adoption among smallholder farmers. Resistance is not always caused by a lack of perceived usefulness, but may arise because the technology is perceived as incompatible with traditional practices, overly complex, or failing to deliver economic benefits that are quickly visible. In this context, the attribute of relative advantage from DOI must be analyzed in conjunction with performance expectancy from UTAUT and perceived usefulness from TAM in order to understand how farmers compare the benefits of technology against the risks they must bear. This integration also opens analytical space for examining economic risk factors, as smallholder farmers tend to have a high level of risk aversion due to limited household financial buffers.

Accordingly, the development of an integrative DOI–TAM–UTAUT framework can be positioned as a staged and systemic approach to explaining the dynamics of digital technology adoption among smallholder farmers in Indonesia. DOI functions to explain the early phase of diffusion and innovation awareness formation through technology attributes and social networks; TAM deepens the analysis at the level of individual perception regarding usefulness and ease of use; while UTAUT connects these perceptions to actual behavioral intention and use within the context of social influence and facilitating conditions. This integrative approach enables a more comprehensive analysis of the cognitive, social, structural, and institutional factors that mutually interact in the adoption process. Therefore, the development of a conceptual model based on the integration of all three theories becomes relevant for explaining variations in adoption rates, sustainability of use, and the policy implications of agricultural digitalization in Indonesia in a more critical and contextual manner. This integration not only enriches the theoretical foundation, but also provides a stronger basis for formulating adaptive, inclusive, and sustainable policy intervention strategies to advance the digital transformation of the smallholder agricultural sector.

5. Conclusion

This research concludes that digital technology adoption by smallholder farmers in Indonesia is a complex, multidimensional, and adaptive socio-technical process. Adoption decisions are not solely determined by the availability of technology or internet penetration, but by the simultaneous interaction of individual capacity, socio-community dynamics, household economic stability, digital infrastructure readiness, and institutional and public policy support.

The integration of the Diffusion of Innovation (DOI), Technology Acceptance Model (TAM), and Unified Theory of Acceptance and Use of Technology (UTAUT) theories demonstrates that each model makes an important conceptual contribution, yet is partial in nature when used alone in the smallholder agricultural context. DOI is effective in explaining the spread of innovation and the role of technology attributes, but does not adequately capture economic risks and structural barriers. TAM helps in understanding perceptions of usefulness and ease of use, but is overly individualistic. UTAUT offers a more comprehensive framework through the dimensions of social influence and facilitating conditions, yet still requires contextual adaptation to explain the collective dynamics of farmer groups and digital access inequality in rural areas.

Based on theoretical synthesis and cross-country empirical evidence from developing nations, this study develops the Adaptive Socio-Technical Agrarian Digitalization Model (ASTAD) as a more contextually relevant conceptual framework for Indonesia. The ASTAD model emphasizes that digital technology adoption is a dynamic adaptive process influenced by five primary layers, namely: (1) farmers' cognitive capacity and digital learning, (2) social capital and collective trust of farmer groups, (3) household economic risk resilience, (4) digital access stability and platform suitability, and (5) policy coherence and market integration. These five dimensions interact within a circular reinforcement system, such that the success of adoption is highly dependent on the balance and synergy among its elements.

The primary implication of this research is that agricultural digitalization cannot be reduced to a program of application or device distribution alone. Inclusive digital transformation requires a systemic approach encompassing the enhancement of digital literacy, strengthening of farmer economic capacity, development of equitable infrastructure, integration of digital services with hybrid advisory support (digital–human), and consistent, data-driven policy. Without this integrative approach, technology adoption risks being partial, unsustainable, and even widening the inequality gap among farmers.

Theoretically, this research contributes to the reinforcement of agricultural technology adoption literature by offering a conceptual model that is more adaptive and contextually relevant for developing countries. Practically, these findings provide a basis for formulating more inclusive, sustainable agricultural digitalization strategies in Indonesia, oriented toward the long-term improvement of smallholder farmer welfare.

6. References

Abdulai, A.-R., Tetteh Quarshie, P., Duncan, E., & Fraser, E. (2023). Is agricultural digitization a reality among smallholder farmers in Africa? Unpacking farmers' lived realities of engagement with digital tools and services in rural Northern Ghana. *Agriculture & Food Security*, *12*(1), 11. https://doi.org/10.1186/s40066-023-00416-6

Alant, B. P. (2021). A case study of the relationship between smallholder farmers' ICT literacy levels and demographic data w.r.t. their use and adoption of ICT for weather forecasting. *Heliyon*, *7*(3). https://doi.org/10.1016/j.heliyon.2021.e06403

Arangurí, M., Mera, H., Noblecilla, W., & Lucini, C. (2025). Digital Literacy and Technology Adoption in Agriculture: A Systematic Review of Factors and Strategies. *AgriEngineering*, *7*(9), 296. https://doi.org/10.3390/agriengineering7090296

Choruma, D. J. (2024). Digitalisation in agriculture: A scoping review of technologies in practice, challenges, and opportunities for smallholder farmers in sub-saharan africa. In *Journal of Agriculture and Food Research* (Vol. 18). https://doi.org/10.1016/j.jafr.2024.101286

Clapp, J., & Ruder, S.-L. (2020). Precision Technologies for Agriculture: Digital Farming, Gene-Edited Crops, and the Politics of Sustainability. *Global Environmental Politics*, *20*(3), 49–69. https://doi.org/10.1162/glep_a_00566

Davis, F. D. (1989a). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS Quarterly*, *13*(3), 319. https://doi.org/10.2307/249008

Davis, F. D. (1989b). Technology acceptance model: TAM. In *Information Seeking Behavior and Technology Adoption* (pp. 205–219). IGI Global.

Ding, J. (2022). The effects of combined digital and human advisory services on reducing nitrogen fertilizer use: lessons from China's national research programs on low carbon agriculture. *International Journal of Agricultural Sustainability*, *20*(6), 1136–1149. https://doi.org/10.1080/14735903.2022.2057643

Fardani, I., Chofyan, I., & Noormansyah, Z. (2024). Digitalisasi Pertanian Melalui Sistem Informasi Pertanian. *Jurnal Pengabdian Masyarakat Borneo*, *8*(2), 131–137. https://doi.org/10.35334/jpmb.v8i2.4440

Feder, G., Just, R. E., & Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic Development and Cultural Change*, *33*(2), 255–298. https://www.jstor.org/stable/1153228

Gizachew, F. (2024). Digital tools and welfare: adoption determinants among ginger producers in Southern and Central Ethiopia. *Frontiers in Sustainable Food Systems*, *8*. https://doi.org/10.3389/fsufs.2024.1443775

Gumbi, N., Gumbi, L., & Twinomurinzi, H. (2023). Towards Sustainable Digital Agriculture for Smallholder Farmers: A Systematic Literature Review. *Sustainability*, *15*(16), 12530. https://doi.org/10.3390/su151612530

Kitole, F. A. (2024). Digitalization and agricultural transformation in developing countries: Empirical evidence from Tanzania agriculture sector. *Smart Agricultural Technology*, *7*. https://doi.org/10.1016/j.atech.2023.100379

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS: Wageningen Journal of Life Sciences*, *90–91*(1), 1–16. https://doi.org/10.1016/j.njas.2019.100315

Marikyan, D., Papagiannidis, S., & Stewart, G. (2023). Technology acceptance research: Meta-analysis. *Journal of Information Science*. https://doi.org/10.1177/01655515231191177

Martha, G. B., Alves, E., & Contini, E. (2012). Land-saving approaches and beef production growth in Brazil. *Agricultural Systems*, *110*, 173–177. https://doi.org/10.1016/j.agsy.2012.03.001

Montes de Oca Munguia, O., Pannell, D. J., & Llewellyn, R. (2021). Understanding the adoption of innovations in agriculture: A review of selected conceptual models. *Agronomy*, *11*(1), 139.

Mushi, G. E. (2022). Digital Technology and Services for Sustainable Agriculture in Tanzania: A Literature Review. In *Sustainability Switzerland* (Vol. 14, Issue 4). https://doi.org/10.3390/su14042415

Nagy, A. S., Arie, F. V., Tuegeh, O. D. M., Bittner, B., & Tumiwa, J. R. (2025). Fintech adoption for SMEs in different socioeconomic contexts: evidence from Hungary and Indonesia. *Financial Innovation*, *11*(1), 131. https://doi.org/10.1186/s40854-025-00876-8

Nxumalo, G. S., & Chauke, H. (2025). Challenges and opportunities in smallholder agriculture digitization in South Africa. *Frontiers in Sustainable Food Systems*, *9*, 1583224. https://doi.org/10.3389/fsufs.2025.1583224

Omulo, G. (2020). Farmer-to-farmer digital network as a strategy to strengthen agricultural performance in Kenya: A research note on 'Wefarm' platform. *Technological Forecasting and Social Change*, *158*. https://doi.org/10.1016/j.techfore.2020.120120

Orr, G. (2003). *Diffusion of innovations, by Everett Rogers (1995)*. Stanford University. https://web.stanford.edu/class/symbsys205/Diffusion of Innovations.htm

Oyinbo, O. (2020). Design of Digital Agricultural Extension Tools: Perspectives from Extension Agents in Nigeria. *Journal of Agricultural Economics*, *71*(3), 798–815. https://doi.org/10.1111/1477-9552.12371

Rotz, S., Duncan, E., Small, M., Botschner, J., Dara, R., Mosby, I., Reed, M., & Fraser, E. D. G. (2019). The Politics of Digital Agricultural Technologies: A Preliminary Review. *Sociologia Ruralis*, *59*(2), 203–229. https://doi.org/10.1111/soru.12233

Rusliyadi, M., Ardi, Y. W. Y., & Winarno, K. (2023). The factors influencing technology adoption process of farmers in term of agricultural extension policy case in Central Java Indonesia. *Agrisocionomics: Jurnal Sosial Ekonomi Pertanian*, *7*(2), 250–260. https://doi.org/10.14710/agrisocionomics.v7i2.16147

Sasmita, H. O. (2026). Factors Influencing Digital Technology Adoption among Young Farmers in Indonesia. *Journal of Agricultural Extension*, *30*(1), 94–105. https://journal.aesonnigeria.org/index.php/jae/article/view/5961

Satria, D., Maghraby, W., & Setyanti, A. M. (2025). Digital Agricultural Technology for Smallholder Farmers: Barriers and Opportunities in Indonesia. *SOCA: Jurnal Sosial Ekonomi Pertanian*, *18*(3), 267–279. https://doi.org/10.24843/SOCA.2024.v18.i03.p01

Sihombing, M. T., Hubeis, M., & Cahyadi, E. R. (2024). Analisis Adopsi dan Penggunaan Aplikasi Pertanian Digital oleh Petani Skala Kecil di Kabupaten Tuban dengan Model UTAUT. *MANAJEMEN IKM: Jurnal Manajemen Pengembangan Industri Kecil Menengah*, *19*(2), 78–90. https://doi.org/10.29244/mikm.19.2.78-90

Silvestri, S. (2021). Going digital in agriculture: how radio and SMS can scale-up smallholder participation in legume-based sustainable agricultural intensification practices and technologies in Tanzania. *International Journal of Agricultural Sustainability*, *19*(5), 583–594. https://doi.org/10.1080/14735903.2020.1750796

Singh, A. (2022). Diagnosing Data from ICTs to Provide Focused Assistance in Agricultural Adoptions. In *ACM International Conference Proceeding Series*. https://doi.org/10.1145/3572334.3572400

Trendov, N. M., Varas, S., & Zeng, M. (2019). *Digital technologies in agriculture and rural areas*. FAO.

Tumiwa, J. R., & Tuegeh, O. D. M. (2025). Adoption of E-Commerce Technology Among Young Agro-Entrepreneurs in Coastal Manado: An Analysis Using the Technology Acceptance Model (TAM). *Jurnal Agroekoteknologi Terapan (JAT)*, *6*(1), 95–109. https://doi.org/10.35791/jat.v6i1.62192

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User Acceptance of Information Technology: Toward A Unified View1. *MIS Quarterly*, *27*(3), 425–478. https://doi.org/10.2307/30036540

Xu, A., Radzi, N. A. M., Liu, Y., & Sieng, L. W. (2026). The Role of Digital Literacy in Agricultural Technology Adoption and Efficiency: A Systematic Literature Review. *Sustainability*, *18*(2), 1138. https://doi.org/10.3390/su18021138