



RESEARCH ARTICLE

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A PROCESS-ORIENTED CONCEPTUAL FRAMEWORK FOR DIGITAL AGRICULTURE ADOPTION AMONG SMALLHOLDER FARMERS

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ABSTRACT

Digital agriculture is increasingly promoted as a key pathway for transforming smallholder farming systems through improved productivity, sustainability and climate resilience. Despite this promise, the adoption of digital technologies among smallholder farmers remains uneven, fragmented and strongly shaped by local contexts. Much of the existing literature explains these patterns using variable-driven and technology-centric adoption models, which offer limited insight into the social, institutional and learning processes through which farmers engage with digital innovations over time. This paper develops a process-oriented conceptual framework to explain how digital agriculture contributes to smallholder farmer empowerment through interacting socio-technical mechanisms rather than isolated adoption determinants. Drawing on Diffusion of Innovations (DOI) theory and informed by agricultural innovation systems and empowerment perspectives, the framework integrates four interrelated layers: contextual conditions, enabling mechanisms, innovation adoption processes and integrated empowerment outcomes. The framework is developed through a systematic synthesis of high-impact literature and is empirically informed by qualitative insights from a multiple-case study of smallholder paddy farmers in Kedah, Malaysia. The framework reconceptualizes digital agriculture adoption as an iterative and socially mediated process shaped by digital literacy, estate-based collaboration and knowledge transfer and mediation. Rather than treating productivity, market access and climate resilience as separate endpoints, empowerment is conceptualized as a capability-based outcome reflected in enhanced agency, decision-making capacity and adaptive resilience. By repositioning DOI as a process theory embedded within socio-institutional contexts, this study provides a theoretically grounded and context-sensitive lens for understanding digital agriculture adoption among smallholders, with implications for policy design, practice and future research.



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I. INTRODUCTION

Digital agriculture has been increasingly promoted as a fundamental component of the new agricultural revolution. Technologies such as precision farming equipment, digital advisory services and data-driven decision support systems are increasingly advocated for their capacity to increase agricultural productivity, maintain environment sustainability and improved climate resilience [1], [2], [3]. At the international and national level, digitalization is articulated in policy agendas as a strategic move to upgrade food systems through improved operational efficiencies and greater participation of smallholder farmers [4], [5]. However, the practical integration of smallholder farmers into digital agriculture ecosystems remains inconsistent and uneven. Empirical studies conducted across diverse regional contexts consistently report persistent challenges related to limited digital literacy, inadequate institutional support and restricted access to collaborative infrastructures [5], [6]. As a result, adoption often occurs in fragmented or symbolic forms rather than through sustained and meaningful use. In many smallholder-dominated agricultural settings, the benefits of digital technologies tend to accrue disproportionately to estate-based or large-scale farms, while smaller producers experience weak spill-over effects and minimal long-term capacity development [1], [7]. A central limitation within the existing body of literature concerns how digital agriculture adoption is conceptualized. Much of the prior research relies on variable-driven and technology-centric models that explain adoption primarily through isolated determinants such as cost, access or technical competence [8], [9]. Although these approaches offer valuable insights into structural barriers, they provide only a partial understanding of the social, institutional and process-oriented dynamics through which farmers interpret, experiment with and embed digital innovations into everyday farming practices. Emerging qualitative and mixed-method studies, including research involving smallholder paddy farmers in Southeast Asia, suggest that adoption decisions are shaped less by technological attributes alone and more by interrelated factors such as digital literacy, collaborative arrangements and trust in institutional actors [10], [11]. These findings point to the importance of viewing digital agriculture adoption as a socially mediated and institutionally embedded process rather than a purely technical choice. In response to these gaps, this study proposes a process-oriented conceptual framework that integrates Diffusion of Innovations theory with estate-based collaboration and broader socio-institutional enablers to explain how digital agriculture contributes to smallholder farmer empowerment. Rather than focusing solely on adoption rates or discrete outcomes, the framework emphasizes the mechanisms, interactions and contextual conditions through which farmers engage with digital technologies over time [2], [12].

II. LIMITATIONS OF EXISTING DIGITAL AGRICULTURE ADOPTION MODELS

II.1 TECHNOLOGY-CENTRIC AND LINEAR BIASES

A substantial body of research on digital agriculture prioritizes technological efficiency, automation and data optimization, often assuming that improvements in technological performance will translate directly into adoption and impact [1], [2]. Such technology-centric perspectives tend to frame innovation uptake as a linear process driven primarily by technical superiority and economic rationality. However, this assumption overlooks the socio-cultural and institutional realities of smallholder farming systems, where decision-making is embedded within collective norms, informal knowledge networks and risk-sharing arrangements [13], [14]. In smallholder contexts, farming decisions are rarely based solely on efficiency gains. Instead, adoption is shaped by trust, social learning, peer influence and institutional legitimacy. Models that neglect these dimensions risk oversimplifying adoption behavior and misrepresenting the mechanisms through which digital technologies are interpreted and integrated into everyday farming practices [10], [15].

II.1.1 *Fragmented Treatment of Adoption Outcomes*

Existing digital agriculture studies frequently isolate outcomes such as productivity, market access or climate resilience, treating them as discrete endpoints of adoption [7], [16]. While analytically convenient, this fragmented treatment obscures the interdependencies among production efficiency, market participation and adaptive capacity, particularly in smallholder systems where these outcomes co-evolve over time. Empirical evidence from agrifood systems research indicates that improvements in productivity do not automatically translate into enhanced market access or climate resilience. Instead, these outcomes are mediated by institutional arrangements, learning processes and access to collective infrastructures [7], [17]. As a result, outcome-focused adoption models fail to capture the cumulative and processual nature of digital agriculture impacts in resource-constrained environments.

II.1.2 *Limited Attention to Institutional and Collaborative Structures*

Although recent studies increasingly acknowledge the role of extension services, advisory systems and knowledge intermediaries, these elements are often treated as background conditions rather than central mechanisms shaping adoption trajectories [15], [18]. Such framing underestimates the importance of institutional mediation, coordination and brokerage in enabling learning and reducing uncertainty among smallholder farmers. Insights from agricultural innovation systems research demonstrate that collaboration, coordination and intermediary actors play a decisive role in facilitating innovation, particularly in contexts characterized by fragmented resources and asymmetric access to information [13], [19]. Estate-based collaboration, cooperative arrangements and innovation brokers function not merely as support structures but as active enablers that shape how innovations are trialed, validated and sustained over time. The marginalization of these mechanisms in dominant adoption models contributes to their limited explanatory power in smallholder-dominated agricultural systems [2], [12].

II.2 DIFFUSION OF INNOVATIONS AS A PROCESS THEORY

Diffusion of Innovations (DOI) theory has long been applied to explain the adoption of agricultural technologies. In much of the digital agriculture literature, DOI is operationalized primarily as a set of innovation attributes such as relative advantage, compatibility, complexity, trialability and observability used to predict adoption likelihood [20].

While this attribute-based interpretation has generated valuable empirical insights, it represents only a partial reading of the theory. In its original formulation, DOI emphasizes diffusion as a communication-driven and socially embedded process, shaped by interactions among actors, social systems and temporal dynamics rather than by individual decision-making alone [20]. Adoption is conceptualized as an iterative process involving awareness, persuasion, experimentation and confirmation, unfolding through social learning and peer influence over time. However, this processual dimension is frequently underemphasized in contemporary digital agriculture studies, where DOI is reduced to a static behavioral model [2]. In smallholder farming contexts, innovation adoption rarely follows a purely rational or individualistic logic. Farmers' perceptions of relative advantage, compatibility and complexity are constructed collectively through observation, discussion and shared experimentation rather than through isolated evaluation [10]. Observability and trialability are particularly critical in reducing perceived risk, especially in environments characterized by income volatility, climate uncertainty and limited institutional safety nets [15]. These dynamics highlight the limitations of treating DOI attributes as independent predictors divorced from social context. Recent scholarship calls for repositioning DOI as a process theory embedded within broader socio-technical and institutional systems. Studies on digital agriculture and agriculture 4.0 demonstrate that adoption trajectories are shaped by trust in intermediaries, access to collaborative infrastructures and institutional endorsement, rather than by technological characteristics alone [2], [12]. Within such systems, learning is cumulative, mediated and contingent on repeated interaction rather than instantaneous adoption. By reframing DOI as a socially mediated learning process, this study aligns with emerging perspectives that integrate diffusion theory with agricultural innovation systems and institutional analysis. This interpretation enables a more nuanced understanding of how digital technologies are interpreted, adapted and sustained in smallholder settings, particularly when adoption is facilitated through collective arrangements and knowledge mediation rather than individual uptake. This process-oriented reading of DOI provides the theoretical foundation for the conceptual framework developed in the subsequent sections.

II.3. METHODOLOGICAL APPROACH TO FRAMEWORK DEVELOPMENT

This study adopts a conceptual research design grounded in the systematic synthesis of high-impact peer-reviewed literature, consistent with established approaches to case-based and theory-building research that emphasize analytical generalization rather than statistical inference [21]. Rather than generating primary empirical data, the objective of this methodological approach is to integrate and reorganize existing theoretical and empirical insights into a coherent, process-oriented conceptual framework that explains digital agriculture adoption among smallholder farmers. The framework development followed an iterative and integrative process comprising three interrelated stages. First, dominant digital agriculture adoption models were systematically examined to identify their theoretical assumptions, analytical focus and conceptual limitations, particularly with respect to their treatment of adoption as a linear and variable-driven outcome [2], [8]. This critical mapping enabled the identification of recurring gaps related to social learning, institutional mediation and collaborative dynamics.

Second, Diffusion of Innovations theory was integrated with perspectives from agricultural innovation systems and socio-institutional analysis to reposition adoption as a socially embedded and processual phenomenon [13], [19], [20]. This integration emphasized the role of intermediaries, collective experimentation and coordination mechanisms in shaping how digital technologies are interpreted, trialed and sustained within smallholder contexts. Third, the conceptual structure was informed by empirical insights reported in recent qualitative studies focusing on smallholder farming systems, particularly within Southeast Asia, to enhance contextual relevance without overgeneralization [10], [11]. These studies provided grounded illustrations of how digital literacy, estate-based collaboration and knowledge mediation interact to condition adoption trajectories over time. Throughout this process, the framework was refined through repeated comparison across theoretical strands, empirical contexts and analytical levels. The resulting framework does not seek to predict adoption outcomes quantitatively; rather, it offers an explanatory and integrative lens that captures the mechanisms, interactions and contextual conditions through which digital agriculture contributes to smallholder farmer empowerment.

II.3.1 Contribution and Novelty

This study contributes to the digital agriculture literature by advancing a process-oriented conceptual framework that moves beyond dominant variable-driven and technology-centric adoption models. While existing research has extensively examined adoption determinants and isolated performance outcomes such as productivity, market access or climate resilience, these approaches often treat adoption as a static decision and overlook the institutional, collaborative and learning processes through which smallholder farmers engage with digital technologies over time [2], [7], [8]. The primary theoretical contribution of this study lies in repositioning Diffusion of Innovations as a dynamic process theory embedded within socio-institutional systems, rather than as a set of independent innovation attributes predicting adoption likelihood [20]. By emphasizing communication, collective experimentation and temporal learning dynamics, the framework aligns diffusion processes with the lived realities of smallholder farming systems, where adoption unfolds incrementally through interaction and mediation [10], [15]. A second contribution is the explicit integration of estate-based collaboration, digital literacy and knowledge mediation as enabling mechanisms that condition adoption trajectories. Prior studies acknowledge these factors individually; however, they are rarely theorized as interacting capacities that jointly enable or constrain diffusion processes in smallholder contexts [11], [13], [19]. By situating these mechanisms within the adoption process rather than treating them as exogenous conditions, the framework offers a more coherent explanation of how digital technologies are trialed, validated and sustained. The novelty of the proposed framework is further reflected in its conceptualization of empowerment as an integrated, capability-based outcome. Drawing on capability and empowerment perspectives, empowerment is framed as enhanced agency, decision-making capacity and adaptive resilience across production, market participation and climate response, rather than as fragmented performance indicators [22], [23]. This reframing addresses a key limitation in digital agriculture research, where outcomes are often evaluated in isolation and disconnected from farmers' long-term capacities. Anchored in empirical insights from recent qualitative studies of smallholder paddy farmers in Southeast Asia, the framework provides a context-sensitive yet transferable analytical lens applicable across diverse smallholder settings [10], [11].

Collectively, these contributions offer theoretical and practical value for researchers, policymakers and practitioners seeking to design inclusive, resilient and institutionally grounded digital agriculture interventions. Table 1 summarizes how the proposed conceptual framework is theoretically anchored in established literature across diffusion theory, innovation systems, digital agriculture and empowerment studies, demonstrating the integrative role of each reference cluster.

III. MATERIALS AND METHODS

Write in detail the research project, including background and limitations. The selection of materials and methods, procedures and equipment must be justified so that the work can be reproduced. Modifications or new methods must be described in detail. You must clearly define the universe and specify how the sample was selected and why it is representative. Data processing represents the practical development of a theoretical basis, deriving the model equations to program the calculation algorithm, according to the need. In materials, they include the technical specifications and the quantities, the origin and, if necessary, the method for its elaboration.

Table 1: Summarize The Establishment Of Proposed Conceptual Framework.

Framework Component	Role in the Conceptual Framework	Supporting References
Contextual Layer (smallholder ecosystem, climate, institutions)	Defines the structural and environmental boundary conditions that shape farmers' risk perceptions, learning capacity and engagement with digital agriculture	[4], [5], [6], [7], [24]
Digital Literacy	Represents the cognitive and practical capability required to access, interpret and apply digital information in farm-level decision-making	[4], [8], [9], [11]
Estate-Based Collaboration	Collective mechanism enabling shared access to technology, joint experimentation, risk reduction and social learning	[10], [13], [18], [19]
Knowledge Transfer and Mediation	Role of intermediaries (extension services, innovation brokers, advisory systems) in facilitating learning, trust-building and interpretation of digital innovations.	[14], [15], [18], [25]
Innovation Adoption Processes (DOI)	Iterative processes of evaluation, trial, observation and learning through which digital technologies are diffused and adapted	[2], [10], [15], [20]
Socio-Institutional Dynamics	Governance structures, power relations, data ethics and institutional arrangements shaping innovation trajectories	[6], [12], [26], [27]
Integrated Empowerment Outcome	Capability-based outcome reflected in enhanced agency, decision-making capacity, market engagement and climate resilience	[7], [16], [22], [23]
Responsible and Inclusive Digital Agriculture	Normative justification for inclusive, ethical and sustainability-oriented digital agriculture interventions	[1], [2], [12], [28]

Source: Authors, (2026).

Within socio-institutional contexts and mediated by collaborative arrangements, rather than driven solely by individual assessment. The final layer captures integrated empowerment outcomes, conceptualized as enhanced agency, decision-making capacity and adaptive resilience across production, market participation and climate response. This outcome is understood as cumulative and capability-based, emerging through sustained engagement with digital technologies and supportive institutional arrangements rather than through short-term technological interventions [22], [23]. Together, the proposed framework provides an explanatory lens for understanding how digital agriculture adoption unfolds as a socially embedded and institutionally mediated process in smallholder systems. Figure 1 illustrates the structure of the framework and the dynamic relationships among its constituent layers.

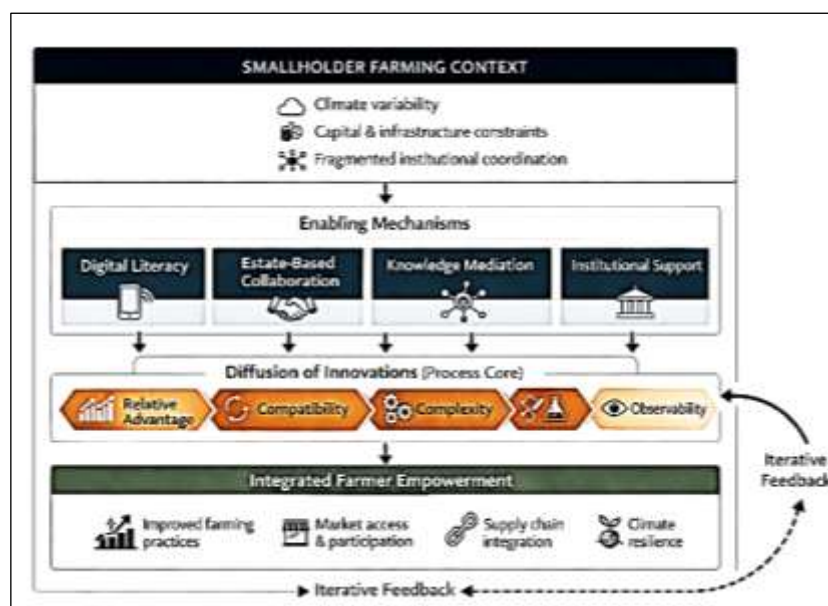


Figure 1: A process-oriented conceptual framework for digital agriculture adoption among smallholder farmer.

Source: Authors, (2026).

III.1 CONTEXTUAL LAYER

The contextual layer situates digital agriculture adoption within the structural, environmental and institutional conditions that shape smallholder farming systems. These conditions include climate variability, fragmented landholdings, income volatility, ageing farmer populations and uneven access to institutional support. Rather than functioning as a passive backdrop, context is conceptualized as an active boundary condition that influences farmers' risk perceptions, learning behaviour and capacity to engage with digital technologies [5], [24]. Empirical evidence from smallholder-dominated agricultural systems indicates that climate uncertainty simultaneously increases the perceived relevance of digital tools while constraining farmers' willingness to invest due to financial risk and uncertain returns [14], [16]. In the case of paddy farming systems, seasonal variability and exposure to climate stress heighten interest in weather forecasting applications and digital advisory services, yet adoption remains contingent on institutional reassurance and collective risk-sharing mechanisms [5], [6]. Socio-economic conditions further condition adoption trajectories. Fragmented landholdings, limited access to credit and income instability restrict experimentation with unfamiliar technologies and amplify sensitivity to perceived complexity and potential failure. Demographic factors, particularly ageing farmer populations and generational differences in digital familiarity, shape learning capacity and engagement with digital interfaces [8], [9]. Institutional arrangements play a central role in mediating contextual constraints. The presence or absence of effective extension services, cooperative structures and supportive policy frameworks influences trust, information flows and the legitimacy of digital innovations. Weak institutional coordination exacerbates uncertainty and reinforces risk-averse behaviour, whereas coherent institutional support can partially offset structural constraints by enabling shared learning and collective experimentation [13], [19]. By conceptualizing context as an active and dynamic layer, the framework emphasizes that digital agriculture adoption cannot be understood independently of the ecological, socio-economic and institutional environments in which smallholder farmers operate. These contextual conditions shape not only whether adoption occurs but also how adoption processes unfold over time and interact with enabling mechanisms discussed in the subsequent section.

III.2 ENABLING MECHANISMS

Empirical and theoretical insights indicate that contextual conditions alone do not determine digital agriculture adoption among smallholder farmers. Instead, adoption trajectories are mediated through a set of enabling mechanisms that condition farmers' capacity to engage meaningfully with digital technologies. In the proposed framework, three interacting mechanisms are identified: digital literacy, estate-based collaboration and knowledge transfer and mediation. These mechanisms operate as process enablers, shaping how farmers interpret, trial and sustain digital innovations over time. Digital literacy constitutes a foundational capability influencing farmers' ability to access, interpret and apply digital information in agricultural decision-making. Limited digital skills, age-related constraints and uneven exposure to training restrict engagement with data-driven tools and increase perceived complexity and risk [8], [9]. Conversely, higher levels of digital literacy enhance confidence, facilitate experimentation and enable more informed assessment of relative advantage and compatibility. Importantly, digital literacy is not treated as a static attribute but as a capability that evolves through repeated use, peer interaction and institutional support [11]. Estate-based collaboration functions as a collective mechanism that lowers individual risk and reduces barriers to experimentation. Through shared infrastructure, coordinated trials and collective decision-making, estate managers, cooperatives and lead farmers create environments in which digital technologies can be observed, tested and validated collectively. Such arrangements enhance observability and trialability while mitigating perceived complexity, thereby accelerating learning and diffusion processes [10], [19].

However, the effectiveness of estate-based collaboration is contingent on governance quality, leadership and trust. Weak coordination or unequal power relations can constrain scalability and limit inclusive participation, reflecting broader challenges identified in innovation systems research [13]. Knowledge transfer and mediation play a critical role in shaping perceptions of legitimacy and usefulness. Extension services, innovation brokers and advisory systems act as intermediaries that translate technical information into locally meaningful knowledge, facilitate social learning and build trust between farmers and technology providers [15], [18]. Empirical studies indicate that experiential learning mechanisms such as demonstration plots, field observations and peer-to-peer exchange are more influential than formal training alone in shaping sustained adoption behaviour [10], [15]. These enabling mechanisms do not operate independently. Rather, they function as interacting capacities that jointly shape adoption trajectories. Digital literacy enhances the effectiveness of knowledge mediation; collaborative arrangements create spaces for learning and experimentation; and institutional mediation reinforces trust and legitimacy. By conceptualizing these elements as enabling mechanisms rather than isolated determinants, the framework explains how smallholder farmers navigate uncertainty and gradually integrate digital technologies into everyday farming practices.

III.3 INNOVATION ADOPTION PROCESSES

Within the enabling environment described in the preceding sections, digital agriculture adoption unfolds through innovation adoption processes conceptualized using a process-oriented interpretation of Diffusion of Innovations theory. Adoption is not treated as a binary or instantaneous decision; rather, it is understood as a cyclical and socially mediated process involving evaluation, experimentation, observation and reassessment over time [20]. Farmers' perceptions of relative advantage extend beyond immediate economic returns to include considerations such as labour efficiency, risk reduction and institutional endorsement. Technologies perceived to reduce exposure to climate uncertainty or enhance coordination with estate managers and extension services are more likely to be trialed and sustained, even when short-term financial benefits are uncertain [13], [16]. These perceptions are constructed collectively through discussion, observation and shared experience rather than through individual assessment alone. Compatibility is shaped by alignment with existing farming routines, seasonal calendars, cooperative norms and land management practices. Digital tools that integrate smoothly with established workflows and collective arrangements are perceived as less disruptive and more feasible, whereas technologies requiring substantial behavioural change face resistance, particularly in ageing farming communities [5], [10].

Perceived complexity represents a major barrier in smallholder contexts, especially where digital literacy is limited. However, complexity is not inherent to the technology itself; it is mediated through access to support, opportunities for hands-on experimentation and peer learning. Estate-level trials, demonstration plots and guided experimentation reduce perceived complexity by transforming abstract technical features into observable and manageable practices [15], [19]. Trialability and observability play decisive roles in building trust and reducing perceived risk. Opportunities to test digital tools on a limited scale and observe their use by peers enable farmers to assess performance under local conditions before committing resources. Such processes are particularly important in environments characterized by income volatility and limited safety nets, where the cost of failure is high [6], [10]. Through repeated cycles of evaluation and interaction, adoption processes become embedded within social networks and institutional arrangements. Learning is cumulative, confidence develops incrementally and adoption decisions are continually reassessed in response to changing environmental and institutional conditions. By conceptualizing innovation adoption as an iterative learning process rather than a static choice, the framework captures the dynamic and relational nature of digital agriculture diffusion in smallholder systems.

III.4 INTEGRATED EMPOWERMENT OUTCOME

The final layer of the proposed framework conceptualizes empowerment as an integrated, capability-based outcome that emerges through sustained engagement with digital agriculture, rather than as a set of isolated performance indicators. In contrast to adoption models that evaluate productivity, market access or climate resilience as independent endpoints, empowerment is understood as the cumulative enhancement of farmers' agency, decision-making capacity and adaptive resilience across interconnected domains [22], [23]. Empowerment in this framework is not assumed to arise directly from technology use. Instead, it is shaped through the interaction of contextual conditions, enabling mechanisms and iterative adoption processes. As farmers acquire digital skills, participate in collaborative arrangements and engage in repeated cycles of learning and experimentation, they develop greater confidence in managing production risks, interpreting information and negotiating institutional relationships [10], [11]. These capabilities enable more informed responses to climate variability, improved engagement with markets and greater autonomy in farm-level decision-making. From a process perspective, empowerment unfolds incrementally rather than instantaneously. Early engagement with digital tools may yield limited or uneven benefits; however, over time, sustained participation in digitally enabled and institutionally supported environments contributes to the accumulation of knowledge, trust and adaptive capacity.

This cumulative process aligns with capability-based interpretations of development, where long-term well-being depends on expanding individuals' and communities' freedoms to act rather than on short-term performance gains [22]. Importantly, empowerment outcomes remain contingent on institutional and collaborative support. Without effective mediation, coordination and inclusive governance arrangements, digital agriculture interventions risk reinforcing existing inequalities by disproportionately benefiting better-resourced actors. Conversely, when enabling mechanisms function effectively, digital technologies can support more inclusive and resilient agricultural systems by strengthening smallholder farmers' capacity to adapt, learn and participate meaningfully in digital agrifood ecosystems [2], [12]. By framing empowerment as an integrated and processual outcome, the proposed framework provides a coherent explanation of how digital agriculture adoption contributes to sustainable and inclusive development in smallholder contexts. This interpretation shifts analytical attention from short-term adoption metrics toward the long-term socio-technical processes that underpin meaningful digital transformation.

IV. IMPLICATIONS

IV.1 THEORETICAL IMPLICATIONS

The proposed framework contributes to digital agriculture theory by reframing adoption as a processual and socially embedded phenomenon, rather than as a function of isolated determinants. By repositioning Diffusion of Innovations as a process theory situated within socio-institutional systems, the framework challenges dominant variable-driven models that emphasize static predictors and linear causality [2], [20]. This shift extends diffusion theory by integrating learning dynamics, institutional mediation and collective action as central explanatory mechanisms. Furthermore, by explicitly linking diffusion processes with agricultural innovation systems and capability-based empowerment perspectives, the framework provides a more holistic lens for analyzing digital transformation in smallholder contexts. This integration advances theoretical debates on responsible and inclusive digital agriculture by demonstrating that adoption outcomes cannot be meaningfully separated from institutional arrangements, collaboration structures and knowledge mediation processes [12], [19].

IV.2 POLICY IMPLICATION

The findings suggest that policy interventions focused primarily on technology provision or infrastructure deployment are unlikely to generate sustained impact among smallholder farmers. Instead, effective digital agriculture policy should prioritize capability development and institutional support mechanisms that enable learning, experimentation and collective engagement. Key policy directions include the design of community-based digital literacy programs tailored to smallholder contexts, support for estate-level collaboration and shared digital infrastructure and the strengthening of extension and advisory services as mediators between technology providers and farmers [4], [5]. Policies that foster trust, coordination and inclusive governance can reduce perceived risk and enhance the legitimacy of digital innovations, thereby supporting more equitable adoption trajectories. These implications align with broader national and international digital agriculture agendas, while emphasizing the need to adapt policy instruments to the socio-institutional realities of smallholder-dominated agricultural systems [2], [5].

IV.3 RESEARCH IMPLICATIONS

The proposed framework provides a foundation for future longitudinal and comparative research examining how digital agriculture adoption processes evolve over time and across diverse institutional settings.

By emphasizing processes and mechanisms rather than static outcomes, the framework enables researchers to operationalize adoption trajectories using qualitative, mixed-methods or process-tracing approaches.

V. CONCLUSIONS

This study advances a process-oriented conceptual framework for understanding digital agriculture adoption among smallholder farmers. By integrating Diffusion of Innovations theory with socio-institutional perspectives on collaboration, learning and capability development, the framework moves beyond dominant variable-driven adoption models and offers a more nuanced explanation of how digital technologies are engaged, adapted and sustained in smallholder farming systems. The framework conceptualizes adoption as an iterative and socially mediated process, shaped by contextual conditions, enabling mechanisms and diffusion dynamics over time. Rather than treating productivity, market access and climate resilience as discrete or independent outcomes, the study reframes empowerment as an integrated, capability-based outcome emerging through sustained socio-technical interaction and institutional support. By repositioning Diffusion of Innovations as a process theory embedded within agricultural innovation systems, this study contributes a theoretically grounded and context-sensitive lens for analyzing digital transformation in smallholder contexts. The framework highlights the central role of digital literacy, estate-based collaboration and knowledge mediation in enabling meaningful and inclusive adoption trajectories, particularly in environments characterized by uncertainty and resource constraints. The proposed framework offers practical relevance for researchers, policymakers and practitioners seeking to design inclusive and resilient digital agriculture interventions. By shifting analytical attention from short-term adoption metrics toward long-term learning and empowerment processes, the study provides a foundation for future research and policy initiatives aimed at fostering sustainable digital transformation in smallholder-dominated agricultural systems.

VI. AUTHOR'S CONTRIBUTION

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