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Exploring the Level of Digital Literacy and the Adoption of Precision Farming Technologies Among Smallholder Paddy Farmers in Kedah

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ABSTRACT

Introduction: Digital literacy plays a crucial role in shaping the uptake of precision farming technologies (PFT) among smallholder paddy farmers, particularly in developing countries. In Malaysia, the digital transformation of agriculture is gaining attention, but the readiness and adoption among rural farmers remain uneven. This study investigates how digital literacy influences the adoption of PFT among smallholder farmers in Kedah, focusing on both technological engagement and social learning processes.

Objectives: The study aims to:

a. Measure the level of digital literacy among smallholder paddy farmers.
b. Analyze the extent of adoption of various precision farming technologies.
c. Examine the role of informal learning and peer influence in facilitating technology adoption.

Methods: A qualitative multiple-case study approach was employed, involving 18 purposively selected farmers from three regions in Kedah: Jitra, Kodiang, and Megat Dewa. Data were collected using semi-structured interviews, field observations, and secondary sources including agricultural extension reports. Thematic analysis was conducted based on Yin's case study methodology, with interpretation guided by Rogers' Diffusion of Innovations (DOI) theory.

Results: The study found that most farmers regularly use smartphones for communication and agricultural information. However, the adoption of advanced technologies such as drones, IoT sensors, and GPS-integrated applications remains limited. Key enablers of adoption include peer demonstrations, perceived usefulness, and family support. Conversely, barriers such as low digital confidence, high technology costs, and limited access to formal training hinder wider adoption. Informal peer networks and intergenerational learning emerged as significant pathways for knowledge dissemination.

Conclusions: This research contributes to the rural digital transformation discourse by contextualizing DOI theory within the Malaysian agricultural setting. The findings suggest that peer-led capacity-building initiatives, community-based extension strategies, and inclusive digital literacy programs can significantly enhance technology adoption among rural farmers. Future studies should explore the long-term impacts of digital interventions and assess policy effectiveness in narrowing the rural digital divide.

Keywords: digital literacy, precision farming, smallholder farmers, Kedah, agriculture technology, qualitative study.

INTRODUCTION

Agriculture is a significant component of the economy, society and food security landscape of Malaysia. Paddy cultivation is particularly significant among the various agricultural subsectors because it directly contributes to

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national food resilience and rural livelihoods. Kedah, known as the "rice bowl of Malaysia," continues to lead the charge of rice production in the country, largely spearheaded by smallholders. And yet, these farmers are increasingly confronting a variety of challenges, such as labor shortages, rising input costs, volatile market prices and climate variability [1].

In response to these challenges, the agricultural sector is realizing a digital transformation with a growing interest in precision farming technologies (PFT). These technologies, from unmanned aerial vehicles (drones) and Internet of Things (IoT) devices to decision-support applications, provide opportunities to increase productivity, optimize resource use and improve sustainability [2]. Specifically, the coupling of mobile applications in the hands of growers, along with real-time sensors and GPS-guided equipment, is a game-changer for traditional practices, making decisions more data-driven and improving farm management.

While these technologies may have revolutionized farming, the rate and uptake of PFT adoption are still patchy among smallholders. One of the main elements that drive this adoption is digital literacy, defined as the ability to locate, evaluate, and apply the information and tools present in digital formats [3]. Smartphone penetration and rudimentary internet access is spreading in rural domains, yet the autonomous optimisation of arsenal farm machinery and precision agriculture is often hampered due to lack of digital skills, constraining training and generational differences.

In rural farming communities, informal learning and peer influence is another important aspect of how farmers develop their skills. Peer encouragements through observations of others' success with technology, support from digitally literate family members, or community-led demonstrations is frequently how a farmer will decide to adopt a new practice.

Research Objectives

a. Objectives To measure the level of digital literacy among smallholder paddy farmers in Kedah.

b. To learn about the level of adoption of precision farming technologies of these farmers.

c. To examine the role of informal learning and peer support in developing digital agriculture practices.

Research Questions

a. How are the level of digital literacy of smallholder paddy farmers in Kedah?

b. Are these farmers adopting precision farming technologies?

c. What restricts and enables the uptake of digital agricultural tools?

d. What are the effects of peer networks and informal learning in adopting precision farming technologies?

e. What are the implications of digital literacy for long-term sustainability and resilience in smallholder farming?

This article aims to answer the question of how well smallholder paddy farmers in Kedah are digitally literate. Given these difficulties, the agricultural industry is experiencing a digital transformation, marked by a growing interest in precision farming technologies (PFT). From unmanned aerial vehicles (drones) and Internet of Things (IoT) devices to decision-support applications, these technologies come with promises of increased productivity, improved resource use and greater sustainability [2]. Mobile applications, real-time sensors, GPS (Global Positioning System)-guided equipment are just a few of the things that can change these long-practiced traditions into data-based practices and effective management of the individual farms.

While these technological advancements can improve the uptake of PFT among smallholders and indeed the success of that uptake, the rate of PFT adoption and the success of that adoption still varies widely between PFT. Digital literacy a set of skills required to search for, evaluate and use digital information and tools effectively [3] is one of the most important factors affecting such adoption. Although it is possible to take note of the growth in smartphone penetration and basic internet access in rural areas, the comprehensively and significantly optimal use of these technologies for precision agriculture, is often hindered by limited digital skills, or the absence of tangible training or generational divides between farmers.

Furthermore, informal mechanisms of teaching and peer group influence play a crucial role in rural farming communities. Whether a farmer adopts a new practice is often dependent on seeing others who have been successful with technology, having family members with digital literacy educate them on how to make effective use of technology, or participating in demonstrations led by the community.

LITERATURE REVIEW

The use of precision agriculture technologies in Asia, particularly in ASEAN countries and Malaysia, has been widely studied. Existing studies have emphasized both the technological advantages and the socio-economic and infrastructural barriers to implementation. Researchers have also highlighted the diverse technologies associated with smart agriculture. This review presents recent studies focusing on key findings and trends, linking theoretical constructs, regional case studies and policy frameworks to contextualize the current study.

Central to enabling smart farming are digital literacy and technology access. Digital Agriculture Technologies (DATs) have the potential to enhance productivity and sustainability, but a lack of digital inclusion may widen the divide between smallholder and commercial-scale farms [3]. For example, the Asia Foundation's "Go Digital ASEAN" program has successfully enhanced basic digital skills in rural communities. However, gaps remain in skills needed for more advanced precision agriculture tools. ADB (2023) highlights the ongoing digital divide and stresses the importance of targeted infrastructure investment in rural and marginalized areas.

A. Digital Literacy in Agriculture

Effective adoption of precision agriculture technologies is fundamentally based on digital literacy. This includes the ability to search, evaluate and apply digital information meaningfully particularly important in rural agricultural contexts where digital tools are essential for farm management, market access and extension services. In Southeast Asia, digital skill gaps remain a significant barrier to modernization.

Technologies such as mobile applications, IoT-based monitoring and GPS systems require higher levels of digital literacy. Older or less-educated farmers are often less inclined to use these tools, which slows the diffusion of innovation in the sector [1]. Initiatives like "Go Digital ASEAN" target this challenge by equipping underserved groups (e.g., women and youth) with basic and intermediate digital skills [2]. Still, targeted agricultural training is needed to bridge the gap between basic smartphone use and digital farming.

Studies [23], [24] and [25] show that most farmers use smartphones mainly for messaging or social media rather than data-driven agricultural platforms. This suggests an urgent need to tailor digital literacy training toward real-world agricultural tools such as digital record keeping, weather forecasting and market price tracking. Informal learning and peer influence, especially intergenerational learning from tech-savvy youth to older farmers, also play a key role.

Future policies must ensure digital adoption is meaningful by providing skill-building resources, localized content, technical support and user-friendly technologies. Smart farming depends not just on access, but on the capacity to use these tools effectively in local agricultural and cultural contexts.

B. Precision Farming Technologies (PFT)

Precision Farming Technologies (PFTs) include tools such as drones, IoT sensors, variable-rate applicators and farm management software. These technologies enable greater operational efficiency, reduced input use and lower environmental impact.

Adoption varies widely across ASEAN countries due to differences in policy, funding, infrastructure and farmer education. Malaysia has introduced programs under the Ministry of Agriculture and Food Security (MAFS), including Agropreneur Muda and SMART SBB, to encourage youth involvement and PFT uptake aimed at improving national food security [3]. Adoption remains at the early stage, concentrated in high-value sectors or cooperatives supported by government funding. Vietnam has demonstrated successful public-private partnerships for IoT implementation, enhancing water and pest management in rice farming [4]. Thailand has promoted drone use through subsidies for

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agricultural cooperatives. Despite progress, barriers remain, including high equipment costs, limited technical knowledge, lack of after-sales support and absence of localized digital content [5]. Some regions lack access to broadband or electricity, making it difficult to integrate into digital farming systems. Trust deficits among older farmers and limited digital exposure further hinder adoption. This underscores the need for behavioral change initiatives and awareness campaigns.

To overcome these barriers, structured policy frameworks should include training programs, infrastructure investment and incentives for smallholders. Collaboration among universities, research institutions and agritech startups is also essential. Examples like Vietnam's smart village models illustrate how integrated digital farming can succeed [4], though affordability and financing remain challenges [25].

C. Theoretical Framework: Diffusion of Innovations (DOI)

Rogers' Diffusion of Innovations (DOI) theory explains how new technologies spread within a community. Adoption depends on five key characteristics: relative advantage, compatibility, complexity, trialability and observability. These attributes influence how quickly and widely new technologies are accepted.

In ASEAN agriculture, DOI offers insights into smallholder behavior. Observable benefits such as improved yields and time savings are strong drivers of adoption. Peer demonstrations and perceived ease of use also support uptake. Recent studies in Malaysia and Vietnam confirm that community demonstration plots and farmer cooperatives accelerate the adoption of drones and IoT devices [6].

Trialability, or the ability to test a technology before full adoption, is particularly influential in rural areas. Compatibility with traditional practices and trust in the source of innovation (e.g., peer vs. government) increase adoption likelihood. Meanwhile, complexity especially the technical requirements for digital literacy may deter older or less-educated farmers.

Recent ASEAN initiatives, such as those by Grow Asia and IFAD, combine peer-based learning, financial incentives and tailored training to foster adoption. This study employs DOI as its theoretical lens to examine cultural and social influences on technology adoption and how they shape smallholder digital engagement.

TABLE 1
PREVIOUS RESEARCH ON PRECISION AGRICULTURE ADOPTION

No.	Precision Agriculture Adoption		
	Author(s)	**Year**	**Title**
1	World Bank	2024	Digital Agriculture Technologies Key to Supporting Malaysia's High-Income Ambitions
2	Eco-Business	2023	Making AI Work for Food Security in ASEAN
3	ERIA	2024	Accelerating the Digitalisation of the Agriculture and Food System in the ASEAN Region
4	FAO	2022	IoT and AI in African Agriculture
5	OECD	2021	Smart Farming for Sustainability
6	Ghosh & Bose	2021	Empowering Indian Farmers with ICT
7	Zhang et al.	2020	Digital Farming in China: Policy and Practice
8	Grow Asia	2022	Grow Asia Digital Learning Platforms Report
9	Abdullah et al.	2022	Mobile Technology Usage Among Paddy Farmers in Perlis

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10	Baharin et al.	2023	IoT Implementation Among Malaysian Paddy Farmers: Drones, Obstacles and Opportunities
11	Ismail & Kamarudin	2018	Digital Readiness and Technology Adoption Among Paddy Farmers in Selangor
12	Jamian et al.	2021	Awareness and Adoption of Precision Farming Among Rice Farmers in Malaysia
13	Sulaiman & Rahman	2019	Training and Technology Challenges in Precision Farming Adoption
14	Lim et al.	2021	Smartphone Usage and Farming Information Needs of Paddy Farmers in Malaysia

The review show in table 1, highlights both opportunities and challenges in advancing precision agriculture in Asia, ASEAN and Malaysia. Bridging digital skill gaps, enhancing rural infrastructure and implementing targeted policies are critical for integrating digital agriculture technologies into mainstream farming systems.

METHODS

The current study utilized a multiple-case study methodology based on the methodological framework developed by Yin [25]. The focus was on understanding how smallholder paddy farmers in Kedah perceive and adopt practices of digital literacy and precision farming technologies. Yin's case study method is especially appropriate for "how" and "why" questions in contemporary real-life contexts, particularly when the lines between phenomenon and context are not clear [25].

Smallholder farmers were treated as individual cases situated within broader, collective contexts, which allowed for an understanding of rural agricultural practice in Malaysia. The case study design provided an in-depth understanding of the similarities and differences across the experiences of individual farmers, whilst preserving the integrity of the context. Case Definition and Selection 18 smallholder paddy farmers were purposively selected from Jitra, Kodiang and Megat Dewa stricts in Kedah. This approach compensated for diversity in participants regarding age, experience, education level and exposure to digital tools. Each participant was one case in this multi-case study design. This is consistent with Yin's emphasis on generalizing to theory rather than to the population [26].

A. Data collection

Data were collected via semi-structured interviews, further complemented by field notes and secondary data (e.g., agricultural extension reports). The interview protocol was built around five main constructs:

a. Experience with digital tools

b. Adopted precision technologies types

c. Daily frequency of accessing the Internet

d. Benefits and constraints perceived

e. Peer and social influence on technology adoption

Each interview was approximately 45– 60 minutes long and was conducted in Malay. Interviews were recorded audio, transcribed verbatim and translated, where necessary.

B. Data analysis

Data were analyzed through Yin's analytic strategies of pattern matching and explanation building [25]. Theories of expected propositions were constructed from Diffusion of Innovations and compared with individual patterns observed in cases. We identified convergent and divergent themes using cross-case synthesis.

Validity and Reliability Ensuring the qualitative research has a certain level of rigor can be a difficult task to this study, Yin's four principles of design quality were used:

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a. Triangulation of data sources (interviews, documents, peer observations)

b. Internal validity: by explanation building and pattern matching

c. External validity: through replication logic across cases

d. Reliability: by using a case study protocol and case database [25]

Ethical Consideration, Ethical clearance was obtained from the institutional review board. All subjects provided informed consent and their anonymity and confidentiality were guaranteed across all stages of the study.

FINDINGS & DISCUSSION

We developed a nuanced, context-rich exploration of smallholder farmers' digital literacy and precision farming technology (PFT) adoption in Kedah through the application of Yin's case study framework. This multiple-case design allowed for thematic identification and validation with within-case and cross-case analysis.

These insights deliver real-world evidence and theoretical contributions on the adaptation of Rogers' Diffusion of Innovations (DOI) theory to rural agricultural contexts in Southeast Asia. Information and digital literacy in a networked age.. became not a stable competency but rather a fluid and age-modulated set of skills, heavily indebted to the nature of social networks and informal educational pathways. This is in line with Salemink et al. [32], for whom infrastructural access is not enough due to socio-technical readiness and community-based diffusion strategies.

Worse, the findings contradict conventional wisdom that access to technology equals adoption. Several participants reported being exposed to smartphones and cooperative drone services, but low confidence, fear and lack of technical support made them reluctant or inattentive [24], emphasizing calls for inclusive, hands-on capacity-building strategies as emphasized by van Dijk [26] and ERIA [33]. Support from institutions was sporadic and frequently only aimed at particular cooperatives. But these pockets of success also underscore the unevenness of policy implementation across regions. These results reaffirm the concerns raised by Chen et al. Thus, also see Ghosh et al. [29] and Musa & Fadzil [30], who, in the context of limited access of small holders, found fragmented digital extension services exacerbated the gap experienced by digitally literate small holder's vs digitally excluded ones.

In short, this section reiterates the usefulness of hybrid approaches that marry digital tools with human-centered learning models, adaptive extension services and grassroots trust-building. These findings provide part of the evidence base for context-sensitive digital agriculture frameworks within Malaysia and ASEAN.

This section includes the findings of the multiple-case analysis of 18 smallholder paddy farmers identified in Jitra, Kodiang and Megat Dewa in Kedah. These findings aligned with Yin's analytic framework focusing on within-case descriptions, cross-case synthesis and pattern matching consistent with Rogers' DOI theory.

A. Within-Case Summaries

A Each participant was treated as an embedded unit of analysis. Key attributes including age, digital experience, tools used and perceived constraints were identified, reflecting Yin's approach to preserving case context while extracting comparative insights [25].

Case A (Jitra): Mid-30s, uses WhatsApp for weather and pest alerts; adopted drone spraying via cooperative.

"Saya tengok kawan guna dron, jadi saya pun cuba cepat dan senang."

("I saw my friend using a drone, so I tried it too — it's fast and easy.")

Case B (Kodiang): Aged 60+, limited digital skills; relies on children for app use.

"Anak saya yang setting apps, saya tengok je."

("My child is the one who sets up the apps, I just watch.")

Case C (Megat Dewa): Utilizes GPS-integrated apps for fertilization schedules; learned through peer demonstrations.

"Saya belajar tengok orang lain guna, lepas tu cuba sendiri."

("I learned by watching others use it, then I tried it myself.")

These summaries underscore digital disparities and the influence of age, peer learning and contextual familiarity, consistent with van Dijk [26] and Lim et al. [27]., but the adoption of tools such as drones and social media for promotion differed across the group.

B. Cross-Case Themes and Pattern Matching

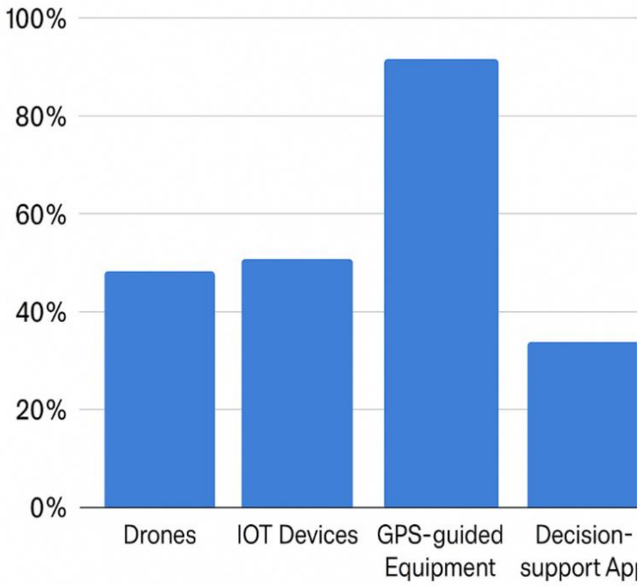

Fig. 1 PFT Adoption Among Smallholder Paddy Farmers in Kedah

Bar chart displays in the Fig 1, show the percentage of farmers who reported using various types of precision farming technologies. GPS-guided equipment (smart phone) was the most adopted (90%), followed by IoT devices and drones (around 50%). Decision-support apps had the lowest usage (15%). The chart highlights uneven adoption across technology types, illustrating preferences and barriers discussed in the text.

Theme 1: Digital Literacy as a Foundational Enabler

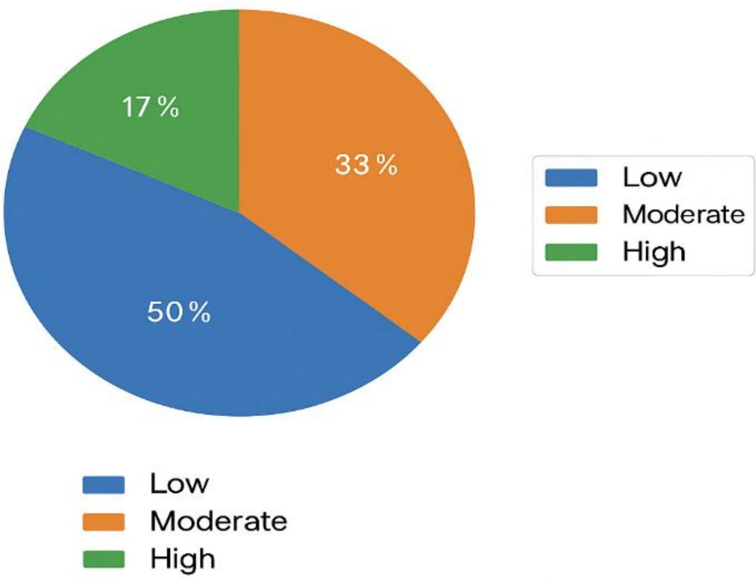

Fig. 2 Digital Literacy Levels Among Smallholder Paddy Farmers (Age ≥ 31)

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The pie chart display in Fig 2. summarizes the digital literacy distribution among smallholder farmers aged 31 and above. Half (50%) of the participants had low digital literacy, 33% demonstrated moderate proficiency and only 17% were highly literate. This visual reinforces the narrative that while smartphones are ubiquitous, advanced digital competency is still unevenly distributed across age groups. Basic digital literacy particularly mobile phone usage was widespread, notably among younger farmers. Smartphone use was primarily limited to apps like WhatsApp and Facebook for communication and agricultural coordination, aligning with Abdullah et al. [28].

> *"Sentiasa guna, tujuan sharing atau sebar maklumat berkaitan penyakit dan baja."*
> *("Always use it, for the purpose of sharing or spreading information related to diseases and fertilizers.") (Participant 4)*
> *"Setiap kali ada serangan, saya akan cari maklumat atau hubungi kawan melalui WhatsApp atau Facebook."*
> *("Whenever there's an outbreak, I will look for information or contact friends through WhatsApp or Facebook.") (Participant 5)*
> *"Saya guna YouTube untuk tengok cara betul guna baja dan racun."*
> *("I use YouTube to watch the correct way to use fertilizers and pesticides.") (Participant 12)*

These quotes reflect a functional but responsive digital literacy. This supports Eshet-Alkalai's [41] multidimensional view of digital skills and Kandel's [42] assertion that peer learning and real-world necessity drive rural digital engagement. Initiatives like Go Digital ASEAN [43] recognize these tools as key gateways into agricultural digitalization.

Theme 2: Adoption of Precision Farming Technologies (PFT)

The uptake of Precision Farming Technologies (PFT) among smallholder farmers in Kedah revealed a multifaceted pattern influenced by relative advantage, accessibility and sociocultural context. Out of 18 participants, 12 actively used PFTs, including drone spraying systems, pest detection sensors and GPS-based field mapping apps. These technologies were primarily introduced through farmer cooperatives or peer influence.

> *"Saya guna dron untuk meracun dan membaja."*
> *("I use a drone for spraying pesticides and fertilizing.") (Participant 2)*
> *"Kami pasang sensor kiraan serangga untuk tahu bila nak sembur racun."*
> *("We installed insect count sensors to know when to spray pesticides.") (Participant 4)*

These responses align with the perceived relative advantage component of Rogers' DOI theory farmers were drawn to time savings and improved spraying efficiency. Studies by Mogili and Deepak [44], Zhang et al. [34] and Wahid and Halim [39] support this, showing that visible productivity gains are essential for encouraging early adoption.

A smaller subset (3 participants) used mobile-based decision-support systems, which suggests compatibility and complexity play a key role. Older farmers often found these tools less intuitive:

> *"Nak kena faham dron, GPS setting, apps... kadang-kadang susah nak adjust."*
> *("You have to understand the drone, GPS settings, and apps... sometimes it's hard to adjust.") (Participant 7)*

This quote underscores what Venkatesh et al. [36] call "perceived ease of use," which often inhibits adoption when digital interfaces are not locally contextualized. Similarly, Balafoutis et al. [47] report that farmers globally face challenges in calibrating drones or interpreting digital pest alerts without training.

One critical dimension in this study was trialability the chance to experiment before full adoption. Many farmers noted they adopted after seeing neighbors succeed:

> *"Saya tengok jiran guna dulu, baru saya berani beli."*
> *("I saw my neighbor use it first, then I had the confidence to buy one.") (Participant 4)*

This affirms the influence of observability, where clear outcomes encourage others. Nguyen et al. [37] and Grow Asia [49] have emphasized that peer-based demonstrations often have higher impact than formal training in smallholder contexts.

Thus, this theme illustrates that while PFTs have clear benefits, adoption is uneven and highly dependent on practical usability, visibility of benefits and social proof. Future extension strategies should therefore focus not only on equipment access but also peer-led workshops, local language interfaces and ongoing support to bridge the usability gap.

Twelve farmers reported using some form of PFT, mostly drones and pest sensors. Adoption was generally based on perceived efficiency and input precision.

> *"Saya guna dron untuk meracun dan membaja."*
> *("I use a drone for spraying pesticides and fertilizing.") (Participant 2)*
> "Kami pasang sensor kiraan serangga untuk tahu bila nak sembur racun."
> ("We installed insect count sensors to know when to spray pesticides.") (Participant 4)
> "Jimat dan bancuhan pun jadi lebih seragam."
> ("It's cost-saving, and the mixture becomes more uniform.") (Participant 10)

These examples support studies by Mogili & Deepak [44], Jamian et al. [45] and Wahid & Halim [39], who emphasize the role of visible efficiency gains in promoting adoption among resource-constrained smallholders.

Theme 3: Peer Influence and Informal Learning

Peer influence and informal learning emerged as powerful forces in the diffusion of digital agriculture tools among smallholder farmers in Kedah. In several cases, participants described how observing their peers' successful use of precision farming technologies influenced their own willingness to adopt similar tools.

> *"Saya tengok jiran guna dulu, baru saya berani beli."*
> *("I saw my neighbor use it first, then I had the confidence to buy one.") (Participant 4)*
> *"Saya belajar tengok orang lain guna, lepas tu cuba sendiri."*
> *("I learned by watching others use it, then I tried it myself.") (Participant 6)*

These experiences highlight the role of observability and trialability two core constructs in Rogers' DOI theory [25]. As Ghosh and Bose [31] observed in the Indian context, peer encouragement and community demonstrations serve as key catalysts for adoption in rural communities lacking formal training mechanisms.

Additionally, intergenerational learning was evident in several accounts, where older farmers relied on younger family members to teach or operate digital applications:

> *"Anak saya yang setting apps, saya tengok je."*
> *("My child is the one who sets up the apps, I just watch.") (Participant 5)*

This aligns with Nguyen et al. [37], who found that informal learning networks particularly within family or close-knit communities are more effective than top-down digital inclusion programs. The findings further echo Man et al. [46], who emphasized the role of cooperative networks and social capital in facilitating technology transfer.

In areas such as Jitra and Megat Dewa, farmer cooperatives provided opportunities for peer-led drone demonstrations. This collective learning environment enhanced trust and reduced perceived complexity, especially for risk-averse farmers. As Setiadi and Yuwono [48] argue, exposure to innovation in socially familiar contexts lowers adoption barriers and builds confidence. However, reliance on informal learning also revealed structural gaps in institutional extension systems. In districts with weak cooperative presence or fragmented support, farmers showed hesitation or lacked sustained engagement with digital technologies. This asymmetry calls for a blended approach supporting grassroots peer influence while ensuring robust public extension services.

In summary, peer influence functioned as both a driver and buffer against risk, validating informal trust-based learning as a crucial factor in smallholder digital transformation.

Peer demonstrations and family support strongly influenced adoption decisions. This echoes Ghosh & Bose [31], who highlight peer networks as critical in informal adoption pathways.

"Saya tengok jiran guna dulu, baru saya berani beli."

> *("I saw my neighbor use it first, then I had the confidence to buy one.") (Participant 4)*
> *"Saya belajar tengok orang lain guna, lepas tu cuba sendiri."*

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("I learned by watching others use it, then I tried it myself.")(Participant 6)

Such experiential learning was also highlighted by Nguyen et al. [37] and Man et al. [46], affirming that trust and visibility often matter more than formal instruction.

C. Explanation Building and Theory Integration

To complement the theoretical analysis, a thematic hierarchical mind map (Figure 1) was developed to visually represent how each of Rogers' core innovation attributes connects with field findings, participant voices and regional literature.

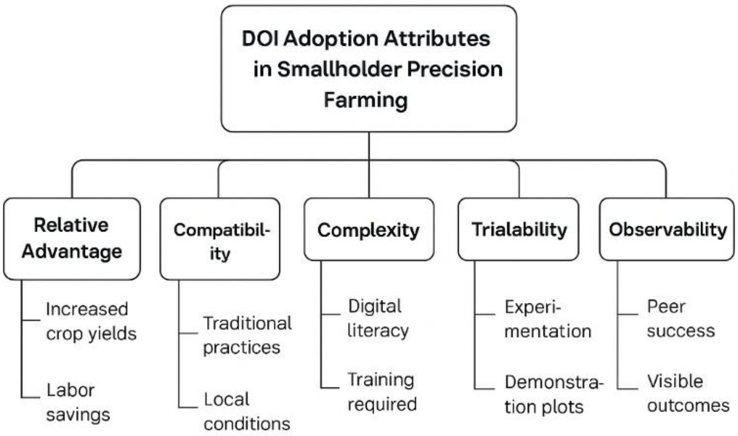

Fig. 3 Thematic Hierarchical Mind Map: DOI Adoption Attributes in Smallholder Precision Farming

The mind map in Fig 3 visually organizes the five Rogers' DOI attributes Relative Advantage, Compatibility, Complexity, Trialability and Observability into a conceptual structure with embedded participant insights and supporting literature. It illustrates how real-life barriers and enablers align with the theoretical framework, offering a clearer understanding of the adoption dynamics among smallholder farmers in Kedah.

Rogers' DOI framework [25] was used as a conceptual lens to systematically interpret how and why certain technologies were adopted or rejected by smallholder farmers across the study areas. The five innovation attributes Relative Advantage, Compatibility, Complexity, Trialability and Observability served as thematic anchors in organizing field data and interpreting patterns that emerged through within-case and cross-case analyses. Each attribute was examined not only as an abstract theoretical construct but grounded in real-world experiences from Kedah's smallholder context. This integration strengthens the empirical utility of DOI theory in rural agricultural settings, echoing calls by Wolfert et al. [35] and Venkatesh et al. [36] to contextualize adoption frameworks in sociotechnical environments.

Moreover, explanation building and pattern matching processes validated the DOI constructs across the three districts (Jitra, Megat Dewa and Kodiang), enabling a clearer interpretation of what Rogers termed the "innovation-decision process." This methodological alignment with Yin's case study protocol also added rigor to the theory-building dimension of this research.

The following analysis demonstrates how each DOI attribute manifested through farmer experiences and is supplemented with participant quotes and scholarly literature to enhance interpretive depth:

1) Relative Advantage: Benefits such as labor savings and precision encouraged adoption.

"Jimat masa membaja dan meracun."
("It saves time in fertilizing and spraying pesticides.")(Participant 3)
"Kerja meracun tak perlu buat sendiri dah, boleh fokus kerja lain."
("I no longer need to do the spraying myself; I can focus on other tasks.") (Participant 6)

Supported by Zhang et al. [34], Wolfert et al. [35] and Li et al. [38].

2) Compatibility: Farmers preferred tools that aligned with daily routines.

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“Saya guna WhatsApp untuk tempah servis racun senang sebab memang dah biasa guna.”
("I use WhatsApp to book spraying services because it's easy and I'm already familiar with it.") (Participant 4)
“Saya lebih selesa guna aplikasi yang dah biasa, macam Facebook dan WhatsApp.”
("I'm more comfortable using apps I'm familiar with, like Facebook and WhatsApp.") (Participant 11)

Aligns with Venkatesh et al. [36] and Ismail & Kamarudin [30].

3) Complexity: Older participants struggled with usability.

“Nak kena faham dron, GPS setting, apps... kadang-kadang susah nak adjust.”
("You have to understand the drone, GPS settings, and apps... sometimes it's hard to adjust.") (Participant 7)
“Bila ada update aplikasi, saya tak tahu nak guna, tunggu anak balik bantu.”
("When there's an app update, I don't know how to use it—I wait for my child to come home and help.") (Participant 5)

Consistent with Balafoutis et al. [47] and Nguyen et al. [37].

4) Trialability: Farmers adopted tech after witnessing peer success.

“Saya belajar tengok orang lain guna, lepas tu cuba sendiri.”
("I learned by watching others use it, then I tried it myself.")(Participant 6)

Supported by Setiadi & Yuwono [48] and Grow Asia [49].

5) Observability: Tangible results increased trust.

“Dron boleh menyeluruh. 90% kawasan.”
("The drone can cover extensively—90% of the area.") (Participant 9)
“Lepas pakai dron, hasil padi nampak lebih sekata dan kurang serangan penyakit.”
("After using the drone, the rice yield appears more uniform and there are fewer disease outbreaks.") (Participant 3)

Echoed by Setiadi & Yuwono [48] and Nguyen et al. [37].

The DOI theory remains valid, but must be adapted for rural Malaysia’s socio-economic landscape. Structural barriers financial, generational and infrastructural are significant influencers, as highlighted by Salemink et al. [32]. [25].

D. Divergent Cases and Anomalies

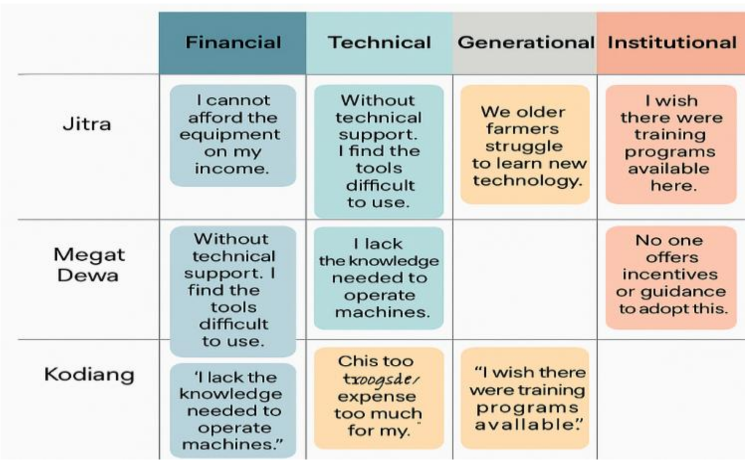

Fig. 4 Farmer Technology Barrier Matrix

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Visual maps in Fig. 4 show the common adoption barriers financial, technical, generational and institutional against farmer quotes and case study locations. It clarifies which constraints appear most frequently and how they intersect across regions, age groups and support levels. Such a matrix helps policymakers identify where support efforts (e.g., training or subsidies) can be most strategically targeted.

Some farmers remained disengaged despite tech access. Barriers included cost, fear of failure and lack of local support.

> *"Kos bateri dron mahal, sampai RM7,000."*
> *("The cost of a drone battery is expensive, up to RM7,000.") (Participant 8)*

These examples underscore what van Dijk [26] refers to as the "second-level digital divide," where usage not just access remains a barrier.

E. Summary of Cross-Case Insight

TABLE 2
THEME OF PFT ADOPTION

No.	Precision Agriculture Adoption		
	Theme	**Common Pattern**	**Divergent Insight**
1	Digital Literacy	Frequent mobile usage by younger farmers	Older users rely on family assistance
2	PFT Adoption	Drone usage in 12 of 18 cases	Cost and complexity hinder 6 participants
3	Peer Learning	Observation drove confidence and experimentation	Less effective in socially isolated farmers
4	Institutional Support	Cooperatives helped in clustered areas	Absent or inconsistent in most rural regions

Based on the table 2 above, findings suggest that adoption of PFT among smallholders is increasing but uneven. A supportive ecosystem involving localized training, peer-led exposure and inclusive policies will be necessary to expand digital farming in Malaysia. These conclusions reinforce recent ASEAN-wide strategies advocating people-centered digital agriculture transformation [33].

CONCLUSION

This study contributes to the understanding of how smallholder paddy farmers in Kedah adopt digital technologies and precision farming tools in a rural Malaysian context. Applying Yin's case study framework and Rogers' Diffusion of Innovations (DOI) theory, this research illuminated how digital literacy, peer influence and institutional support interact to shape farmer behavior.

Findings showed that while smartphone use is widespread, advanced digital skills and the adoption of precision technologies like drones, IoT sensors and decision-support applications remain uneven. Younger farmers, or those with digitally literate family members, were more likely to explore and adopt innovations, especially when peers demonstrated visible success. Conversely, older farmers and those in more isolated regions were less likely to engage without assistance or structured support.

Barriers to adoption were consistent across cases: high costs, technical complexity, generational skill gaps and inconsistent institutional support. These mirror concerns documented by Wahid and Halim [39], Salemink et al. [32] and Nguyen et al. [37], emphasizing the need for more localized, inclusive and hands-on support mechanisms. The use of informal learning, particularly through peer observation, played a strong role in bridging gaps in digital training, validating the value of demonstration plots and community-led initiatives as emphasized in Setiadi and Yuwono [48] and Grow Asia [49].

From a theoretical standpoint, the study confirms the continued relevance of DOI theory, particularly the role of observability, trialability and compatibility in the adoption process. Yet, it also suggests the need to adapt DOI in rural Southeast Asian contexts by accounting for the digital divide, intergenerational dependence and social cohesion.

A. Policy Implications Insight

TABLE 3
POLICY RECOMMENDATION VS ALIGNMENT WITH NAP 2.0

Policy Recommendation	Alignment with NAP 2.0 Goals
Expand access to digital farming tools via targeted subsidies	Increase technology adoption among agropreneurs
Invest in mobile-based extension and training programs	Strengthen digital literacy and human capital
Encourage peer-led demonstration projects	Promote inclusive innovation and participatory learning
Support rural ICT infrastructure development	Bridge urban–rural digital divide and increase connectivity
Foster public–private partnerships in agri-tech support	Stimulate resilient and tech-enabled agricultural value chains

Table 3 above summarizes the identified key policy interventions based on our study results and specifically robust ecosystem services relevant to align with Malaysia's National Agrofood Policy 2021–2030 (NAP 2.0). The things as recommended are meaningfully linked to larger national and international policy narratives around increasing access to technology, closing digital divides and developing resilient agrofood value chains. The proposed actions reiterate the need for smart farming approaches that are inclusive, participatory and supported by infrastructure.

In conclusion, digital transformation in agriculture must not only focus on technology access but also emphasize community dynamics, training and inclusive support systems. Ensuring all smallholders regardless of age or education can actively participate in the digital farming future is essential for equitable and sustainable agricultural development in Malaysia.

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