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Challenges in Adopting Smart Farming Technologies: Insights from Multi-Stakeholders in the Malaysian Paddy Industry

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Abstract. This study explored the multifaceted barriers affecting the adoption of Smart Farming Technologies (SFTs) in Malaysia's paddy sector, using an integrated lens of the Grounded Theory and the Technology–Organization–Environment (TOE) model. This research identified eight interconnected barriers through extensive interviews with various stakeholders, including extension agencies, mill operators, and research entities. Key technological barriers include prohibitive costs, mismatched machinery for local field conditions, and inadequate digital infrastructure. At the organizational level, aging farmers' risk aversion, fragmented smallholdings, and reliance on service providers restrict widespread uptake. Externally, heavy input subsidies and price controls, along with a lack of incentives for technology acquisition, deter meaningful investment in advanced tools such as drones, sensors, or blockchain-based systems. The Grounded Theory approach also illuminated how daily realities such as waterlogged fields, part-time farming, and outsourcing tasks, further complicated the broader transition to smart agriculture. By situating these insights within the TOE framework, the study reveals that effective SFTs adoption requires parallel improvements in technology accessibility, organizational readiness, and supportive policy environments. It emphasizes that any single measure, such as subsidizing new equipment, remains insufficient without corresponding investments in farmer training, data infrastructure, and restructuring of subsidy regimes. These insights provide a deeper understanding of innovation diffusion barriers and suggest targeted interventions, ranging from cooperative financing models to pilot projects for supply-chain segregation, ultimately aiming to revitalize the Malaysian paddy production.

Keywords: Smart Farming Technologies, Smallholder Farmers, TOE Framework, Blockchain, Grounded Theory, Malaysia

1. Introduction

Agriculture is witnessing a profound technological transformation, driven by innovations designed to enhance productivity, sustainability, and profitability (Büyüközkan & Uztürk, 2024). Terms such as "precision agriculture," "digital agriculture," "smart farming," and "Agriculture 4.0" have emerged to represent different aspects of this revolution (Dibbern et al., 2024). For clarity, this research adopts the umbrella term Smart Farming Technologies (SFTs) to encompass these advances and their associated technologies (Osrof et al., 2023).

SFTs optimize resource use, reduce environmental harm, and increase agricultural output by leveraging automation, sensors, drones, data analytics, and mobile applications, among other innovations (Azlan et al., 2024b; da Silveira et al., 2021). Their potential extends across all stages of the agricultural supply chain: seed and genetic development (pre-field), farm-level cultivation and management (in-field), and distribution and processing (post-field) (da Silveira et al., 2021). Yet, adoption patterns vary substantially worldwide due to barriers like high costs, limited connectivity, infrastructural gaps, and low skill levels (FAO, 2022; Ingram et al., 2022). Even within developed economies, adoption rates can be modest. For example, while the U.S. surpasses a 40% adoption rate of certain precision farming tools, Europe remains at around 25% (Schrijver et al., 2016; Hellerstein et al., 2019). In developing nations, uptake is even more constrained (FAO, 2022; Mana et al., 2024).

In Malaysia, the agricultural sector has historically played a central role in economic development. However, its contribution to national GDP dropped to around 7.4% in 2023, trailing behind the services, manufacturing, and mining sectors (The Ministry of Economy, 2023; World Bank, 2024). Structural challenges such as an aging farming population, limited technological adoption, fragmented support systems, and climatic uncertainties, compound this decline (Dardak et al., 2022; Rahman et al., 2023). Despite the availability of various SFTs like drones, irrigation systems, farm automation, and precision farming tools (Diana et al., 2024), Malaysia's smallholder farmers remain largely dependent on traditional methods (Adnan et al., 2022; Danuri et al., 2019). Blockchain technology has also gained increasing attention for its capacity to enhance transparency, traceability, and trust among various actors in the agricultural supply chain (Xu et al., 2020). Using AI and blockchain is seen as a promising way to better predict rice prices and support efforts toward achieving food self-sufficiency (Wiliam et al., 2022). However, the very attributes that make blockchain promising can also pose challenges, such as high setup costs, the need for robust digital infrastructure, and legal and regulatory uncertainties (Tan et al., 2023). In response, government initiatives like the National Fourth Industrial Revolution (4IR) policy (2021–2030), the 12th Malaysia Plan (2021–2025), the Shared Prosperity Vision 2030, and the National Agro-Food Policy (NAP 2.0) emphasize SFTs as essential catalysts for revitalizing agriculture in Malaysia.

Although SFTs present opportunities to increase agricultural output, reduce environmental degradation, and enhance supply chain resilience, they also create challenges for various agriculture stakeholders. Financial investments in hardware (e.g., drones, sensors, or blockchain nodes), the need for digital literacy among farmers, and organizational shifts required within supply chains can be significant hurdles (Osrof et al., 2023; Xu et al., 2020). Adoption of new technologies often involves complex decision-making processes, where stakeholders must evaluate multiple criteria such as cost, performance, and contextual suitability (Lin et al., 2023). Smallholder farmers, who form the backbone of Malaysian agriculture, often lack the resources to invest in advanced technologies (Ahmad et al., 2024; MAFS, 2021). Moreover, inadequate digital infrastructure and fragmented supply chain governance complicate efforts to integrate technologies like blockchain (Ahmad et al., 2024; Tan et al., 2023).

The paddy industry exemplifies these complexities. Rice cultivation in Malaysia is a staple food, yet the country relies on imports to meet about 30–40% of its annual consumption (Zaman et al., 2023). Government agencies such as MADA, KADA, IADA, and PBLS manage large-scale "granary" areas equipped with relatively sophisticated irrigation systems, but these account for only part of the country's

rice production (Dorairaj & Govender, 2023; Rahmat et al., 2019). The strain on food systems, exacerbated by population growth, resource constraints, and disruptions such as the COVID-19 pandemic, amplifies the urgency to modernize agricultural practices (Azlan et al., 2024a; Dorairaj & Govender, 2023). If the underlying challenges of SFTs adoption remain unaddressed, Malaysia's agricultural sector risks stagnation, undermining national goals for food security, export competitiveness, and rural development (Hashim et al., 2024; MAFS, 2021). This imbalance between potential and practical uptake highlights a crucial question: What are the key barriers influencing the adoption of Smart Farming Technologies (SFTs) among stakeholders in Malaysia's paddy industry?

This research offers both academic and practical value. Academically, by integrating Grounded Theory with the TOE framework, the study enriches the literature on agricultural technology adoption, especially in developing-country contexts where both institutional and socio-cultural factors significantly shape outcomes. The empirical evidence from Malaysia's paddy industry highlights how these theoretical constructs align with or differ from real-world experiences. Practically, this research provides concrete evidence to guide policy adjustments for government agencies tasked with modernizing agriculture. Insights into barriers ranging from limited digital infrastructure to minimal farmer training can aid in refining incentive structures, extension services, and regulation. Similarly, agribusiness firms and technology providers can tailor their offerings to fit the capacity and needs of smallholders, thereby increasing the likelihood of successful technology integration. An effective adoption of SFTs can help Malaysian farmers achieve higher yields, improve environmental sustainability, and contribute to national food security goals. By shedding light on the challenges and enablers of such adoption, the study supports broader initiatives within the National Agro-Food Policy 2021–2030 (NAP 2.0) and the Shared Prosperity Vision 2030, fostering resilient rural communities and a more competitive agricultural sector.

2. Literature Review

To address this question, this study incorporates two complementary theoretical lenses underpinning the integration of blockchain technology into smart agriculture supply chains: Grounded Theory and the Technology-Organisation-Environment (TOE) framework. Together, these frameworks provide methodological rigour and conceptual breadth, ensuring the research captures the complexity of technological adoption in agricultural contexts.

2.1 Grounded Theory

Grounded theory is a qualitative research approach that strives to build theory from data collected directly from participants. Grounded theory was first proposed by Glaser and Strauss in the 1960s and later developed into three main strands: Glaserian grounded theory, Straussian grounded theory and constructivist grounded theory. An important aspect of the Glaserian approach is that research should be grounded in an open mind, whereby ideas and categories are allowed to surface organically from the data without predetermined assumptions (Glaser & Strauss, 2017). On the other hand, a more structured and systematic method is offered by the Straussian approach which organizes data into categories and subcategories via formal coding procedures (Strauss & Corbin, 1998). Inspired by these perspectives, Charmaz (2006) developed the constructivist approach which recognizes that the researcher does not play a passive role in interpreting data and appreciates findings as co-constructed through exchanges between researchers and participants (Mitchell, 2014).

This study uses a constructivist grounded theory approach to gain deeper insights into participants' experiences and perspectives. This method seems especially fitting given the comparatively little research on localised obstacles to uptake of smart farming technology (SFT), from relevant stakeholders. Important themes and patterns are identified after an iterative sequence of this data collection, coding, comparison and analysis. Some issues that may stem from the data, illustrating the lived experience of extension officers and farmers, and actors in the supply chain could include limited digital literacy,

resource constraints or facing government support. Engaging with actual practice here offers an opportunity to ground findings in real-life scenarios and also conceptualize and demystify the phenomenon of interest.

2.2 Technology-Organisation-Environment (TOE) Framework

In this study, we also utilised the technology-organisation-environment (TOE) framework as proposed by DePietro et al. (1990), to provide a holistic view of blockchain technology adoption. These are the technology features of innovation, organization where the innovation is applied and environmental factors as external influencers of adoption. The tripartite structure makes TOE particularly relevant for analysing complex innovations like blockchain that necessitate a convergence of technologies, organizations, and projects. In recent literature, the TOE framework has been viewed as the fundamental model to explore innovation adoption and the creation of new value (Chittipaka et al., 2022). Researchers extend TOE into diverse technological domains to describe how organisations assess, adopt and assimilate new technologies. The TOE framework is very much applicable to smart agriculture as in addition to system-level characteristics like security, transparency and scalability, the adoption of this technology also depends on organisation level factors such as readiness and environment (i.e., availability of resources) along with its external environment including market demand pressures, regulatory issues or pressures from supply chain partners. Understanding adoption through the TOE framework, this approach acknowledges that technology advancements are not merely a technical selection but are influenced by organisational and environmental contexts.

3. Methodology

This study employs a qualitative exploratory design, using semi-structured interviews as the primary data collection method. Qualitative research is well-suited for understanding complex social phenomena, particularly when exploring stakeholders' perspectives on Smart Farming Technologies (SFTs) adoption (Creswell & Poth, 2016). The study is informed by Grounded Theory principles, allowing themes to emerge from the data rather than testing pre-established hypotheses (Glaser & Strauss, 2017). The Technology-Organization-Environment (TOE) framework was not imposed on the interview process but served as a conceptual guide for later analysis and discussion (Tornatzky et al., 1990).

The use of semi-structured interviews ensures a balance between structure and flexibility. A core set of guiding questions provided consistency across interviews, while open-ended probing allowed participants to highlight issues, they deemed important. This approach enhances credibility and trustworthiness, ensuring all participants discuss key domains of interest (technology use, farm practices, perceived challenges, etc.) while allowing findings to be deeply grounded in individual experiences (Guba & Lincoln, 1989; Patton, 2014).

Data were collected through in-depth, semi-structured interviews with key agriculture stakeholders within the Malaysian paddy industry. A total of 15 participants were selected using purposive sampling, ensuring representation from multiple key stakeholder groups relevant to SFTs adoption (Patton, 2014). The participant breakdown included:

- Officials from regional paddy management agencies (e.g., IADA – Integrated Agriculture Development Area in Seberang Perak and Penang; MADA – Muda Agricultural Development Authority in Kedah). These individuals provided insights into extension services, mechanization programs, and government support for SFTs adoption.
- Representatives from the national rice corporation (e.g., BERNAS), which oversees milling and distribution. They shared perspectives on post-harvest technology adoption, supply chain integration, and traceability challenges.
- Researchers from MARDI (Malaysian Agricultural Research and Development Institute), who provided expertise on agricultural innovation, research-to-field gaps, adoption barriers, and supply chain traceability challenges.

- Farmers' perspectives were indirectly captured through insights shared by agencies working closely with farmer communities. While direct interviews with farmers were not conducted, participants relayed common concerns and feedback, aligning with recent literature emphasizing multi-stakeholder approaches in SFTs adoption research (Osrof et al., 2023).

Each interview was conducted in person and lasted between 90 and 120 minutes. Depending on the participant's preference, the interviews were conducted in a mix of English and Malay. Audio recording was used with consent, ensuring accuracy in transcription and analysis. Confidentiality was assured to encourage candid discussion about challenges.

An interview guide was developed, covering key themes such as current farming practices and technologies in use, awareness and understanding of SFTs (e.g., knowledge of drones, sensors, blockchain), personal or observed experiences with SFTs adoption, barriers or difficulties faced in implementation, support systems available or lacking, and suggestions for improving adoption rates. While these topics were addressed in all interviews, the semi-structured format allowed the interviewer to probe deeper based on responses. This iterative probing approach enriched the data and captured detailed mechanisms underlying SFTs adoption challenges (Tong et al., 2007).

Data analysis followed a Grounded Theory-informed approach, using thematic analysis to identify recurring patterns and emerging themes (Braun & Clarke, 2006). The constant comparison method was employed, where data were coded iteratively and inductively to refine conceptual categories (Glaser & Strauss, 2017). Open coding was conducted on each transcript, identifying concepts or issues mentioned (e.g., codes like “high machinery cost,” “farmers’ age,” “no internet in field,” “subsidy dependence,” etc.). These initial codes were then compared and grouped into categories representing broader themes, followed by axial coding to explore relationships between themes. A two-stage analysis is implemented in this investigation. In the initial phase of data analysis, Grounded Theory was used as an inductive approach to coding (Gasson 2004; Glaser and Strauss 1967), enabling research themes to emerge from the data without predetermined categories (Schatzman et al. 1992). The Technology–Organization–Environment (TOE) framework is then applied as a lens for interpretation, allowing the structuring and contextualisation of the emergent themes into comprehensive technological, organisational, and environmental factors. This facilitates both the interpretation of theory and the discovery of data.

Several strategies were employed to enhance credibility and trustworthiness. First, findings were triangulated across different stakeholder groups to ensure consistency (Patton, 2014). Next, preliminary themes were shared with selected participants to confirm accuracy and relevance (Guba & Lincoln, 1989). Lastly, the research team maintained reflexive memos to document assumptions and emerging insights during analysis (Creswell & Poth, 2016). The study reached data saturation when no new themes emerged from additional interviews, aligning with best practices in qualitative research (Guest et al., 2006).

4. Analysis and Results

This section presents a structured analysis of interviews with key stakeholders in Malaysia’s paddy industry, highlighting critical barriers and challenges to adopting Smart Farming Technologies (SFTs), including blockchain and other innovations. In line with the grounded theory approach, this study compared codes across all interviews, then consolidated them into eight overarching barrier themes (see Appendix A), ultimately reflecting the TOE (Technology-Organization-Environment) framework. Next, this paper synthesizes these themes and illustrates them with selected participant quotes.

4.1 High Cost and Limited Economic Returns

Across all interviews, high upfront costs for machinery or digital solutions combined with low profit margins emerged as a pivotal barrier. MARDI officials noted that farmers are reluctant to invest if yield gains are not guaranteed. IADA officers in both Penang and Perak observed that for smallholders earning a modest seasonal income, a drone or harvester can seem prohibitively expensive. Meanwhile,

Bernas confirmed that even if mills benefit from certain automations, farmers "don't get more" compensation for improved quality, reinforcing the sense that there is no clear or feasible return on investing in advanced tools. Moreover, while subsidies do offset some costs, they often focus on basic inputs rather than advanced technology, limiting the economic incentive to modernize.

4.2 Older Farmer Demographics and Risk Aversion

All four interviews emphasized the predominance of older farmers managing small plots. These farmers tend to be more risk-averse, reluctant to test unfamiliar equipment, and less confident in digital tools or mobile apps. MADA indicated that only 1.9% of its 54,886 registered farmers are under 30. In Penang, an officer estimated 95% are "very old farmers." This demographic reality dampens adoption, as an entire generation is hesitant to try costly innovations that might fail and reduce their seasonal income. Although youth training programs exist, the enrolled numbers remain small.

4.3 Small / Fragmented Landholdings and Part-Time Farming

One of the most consistent findings was the pervasive fragmentation of farmland—commonly 1–2 hectares per owner—and the prevalence of part-time farmers. MADA data show that less than 4% of farmers have more than 6 hectares. In terms of off-field work, IADA Penang observed that 75% of farmers are engaged in off-field jobs to enhance their sustenance and have a stable income stream. Because SFTs often require economies of scale to justify capital outlays (e.g., drones, laser-leveling equipment), small or scattered plots make it difficult to achieve a financial payoff. Part-time farmers, juggling off-farm jobs, may also have less motivation or availability to attend training or operate new technologies themselves.

4.4 Technological Mismatch and Infrastructure Gaps

Technological barriers go beyond cost alone. Multiple participants (particularly from IADA Penang and Perak) noted that certain imported machines—like large harvesters—are unsuited to waterlogged soils and end up sinking or degrading the soil. Meanwhile, advanced technologies require reliable connectivity and more uniform field layouts. MARDI underscored the lack of "baseline digital data," and that "agriculture is the least sector" to see comprehensive digitization. Even partially automated systems at Bernas mills are not always integrated with farm-level data. These issues reflect both physical conditions (soil, field shape) and digital infrastructure (internet coverage, stable power).

4.5 Low Digital Literacy and Limited Training

This theme concerns the individual capacity of farmers, including their skills, knowledge, and willingness to adopt new technologies in the context of digital capabilities. All agencies reported that farmers typically do not use SFTs like drones, laser-leveling, or Agri apps themselves. Even when IADA or MADA organize extension programs, attendance is low, especially among part-time farmers or those who doubt technology's immediate benefits. MARDI staff expressed concern that many farmers lack formal education or confidence in using new technologies, thus requiring hands-on demonstration. Bernas likewise noted that manual checks remain the norm despite having an automated paddy dryer, partly due to operator habit and partial skepticism toward sensor readings. Without comprehensive training efforts or tech-savvy personnel in rural areas, advanced SFTs adoption stalls.

4.6 Policy and Institutional Barriers

A recurring theme was the misalignment of incentives and a fragmented institutional landscape. Heavy subsidies on seed, fertilizer, and paddy pricing keep farmers afloat but do not specifically reward investments in innovation or quality. Agencies like IADA, MADA, MARDI, and Bernas each have distinct mandates, and participants noted a lack of a unified "end-to-end" modernization drive. MARDI mentioned that government focus can shift each five-year RMK cycle from rice to another crop (like

pineapple), limiting continuity for large-scale digital rollouts. IADA Perak relies on yearly budgets for drone spraying or laser-leveling, which can vary season by season. Such stop-and-go funding and bureaucratic silos create uncertainty and reduce farmer confidence in new technologies.

4.7 Service Provider / Operational Constraints

Regarding the ability and preparedness of service providers to support the adoption of SFT, this issue highlights limitations at both the organisational and implementation levels. Smallholders commonly outsource mechanized tasks (e.g., plowing, spraying, harvesting) to third-party technology service providers (e.g., drones), a practice noted in MADA, IADA Penang, and IADA Perak. While this can lower an individual farmer's upfront cost, it also means the farmers themselves rarely develop direct expertise in newer "smart" methods. If service providers do not see sufficient demand or profit, they may not invest in more advanced equipment—thus further slowing adoption. Additionally, the narrow planting window in paddy cycles can overwhelm the few providers who do offer "smart" services, leading some farmers to default to simpler or traditional approaches.

4.8 Lack of Supply Chain Integration and Traceability

This theme represents system-level coordination challenges among stakeholders, particularly fragmentation and discontinuity in the broader agricultural supply chain. All interviews, particularly MARDI and Bernas, highlighted that blending paddy from many farms is standard practice for efficiency, making it nearly impossible to trace each bag back to an individual plot. This hampers any blockchain or end-to-end digital solution, since data continuity breaks once multiple sources are mixed. MADA and IADA officials, likewise, noted that farm-to-mill data exchange is minimal: farmers deliver paddy, mills weigh it, and records are kept in siloed systems. MARDI also pointed out that the rice supply chain involves many players: seed producers, smallholder farmers, government extension, service providers, rice mills, distributors, retailers. Each player tends to collect data independently and mostly without a digital form. Therefore, advanced traceability remains mostly hypothetical without unified platforms or standardized data collection. As a result, even if technology exists, the overarching chain-of-custody infrastructure is still lacking.

Taken together, these eight themes reveal a deeply interconnected set of barriers. Low profitability and older demographics reinforce each other, as risk-averse farmers see little incentive to invest. Fragmented plots, reliance on service providers, and limited digital literacy exacerbate the difficulty of scaling advanced technologies. Meanwhile, policy constraints, modest training reach, and short funding cycles mean that even promising pilot projects often fail to reach widespread adoption. Lastly, the supply chain, where paddy is blended and each player acts distinctly, undermines traceability-focused solutions such as blockchain.

5. Discussion

The data analysis identified eight interrelated barriers, including high costs, older demographics, policy misalignment, and limited supply-chain integration, which collectively slow or prevent widespread adoption of SFTs. This section discusses the barriers through the Technology–Organization–Environment (TOE) framework to provide a structured understanding of how these barriers emerge and interact, offering deeper insights into these challenges and identifying potential pathways for enhancing SFTs adoption.

5.1 Technological Context

Within the Technology–Organization–Environment (TOE) framework, the technological domain refers to the characteristics of new solutions and their infrastructure requirements (Tornatzky et al., 1990). In the context of SFTs, the findings reveal high costs, limited digital literacy, and infrastructure shortfalls as

significant hurdles. Stakeholders frequently emphasized the prohibitive costs of advanced machinery such as drones, sensors devices, and blockchain implementations. High initial investment combined with minimal financial returns, resulting from controlled rice pricing, creates a situation where technology adoption appears risky and frequently unprofitable (Osrof et al., 2023; Rogers, 2003). Moreover, local conditions such as waterlogged fields undermine the adoption of large harvesters or heavy machinery, implying a mismatch between imported technology and local agronomic realities. Past literature revealed that land locations and conditions can affect the adoption decision of SFTs (Osrof et al., 2023). In parallel, limited internet coverage hinders the viability of IoT-based real-time monitoring, while many farmers lack the requisite digital skills to operate or maintain these systems. The need for baseline data, such as maps, yield records, and soil parameters, further complicates blockchain or AI-driven applications because reliable databases are lacking. These issues are consistent with past studies that argued that "smart" solutions demand both user-friendly interfaces and supportive infrastructure (Klerkx & Rose, 2020). Collectively, the local specificity of the findings implies that one-size-fits-all technologies rarely thrive in smallholder contexts where cost, complexity, and compatibility must be carefully balanced (Dibbern et al., 2024; Osrof et al., 2023).

5.2 Organizational Context

The organizational dimension in TOE addresses internal capabilities, resource availability, and cultural or managerial readiness (Tornatzky et al., 1990). In Malaysia's paddy sector, several patterns emerge that hinder SFTs adoption. First, many farmers are older and exhibit a risk-averse attitude toward new technologies. This situation resonates with the literature and industry reports, indicating that aging smallholders often favor consistency over potentially disruptive changes (FAO, 2022; Osrof et al., 2023). Second, operational fragmentation is common; small plots of one or two hectares offer minimal economies of scale, especially in highly mechanized tasks. Such fragmentation is further complicated by part-time farmers who juggle off-farm jobs and thus have limited bandwidth to master new tools. Relying on service providers for plowing, spraying, and harvesting alleviates initial capital outlay (Anastasiou et al., 2023). However, it also means that actual hands-on exposure to smart farming methods remains low among farmers. This service-provider ecosystem can even inadvertently result in "under-adoption" if providers do not see commercial incentives to upgrade their equipment. From a managerial perspective, adopting a new technology requires not just a purchasing decision, but also internal reorganization: individuals must be trained, record-keeping must integrate digital data, and support mechanisms for troubleshooting must be in place. These facets mirror Rogers (2003) emphasis on how early adopters often need robust knowledge and championing capacity. Without such organizational readiness, even subsidized or donated equipment may sit idle, underscoring how technology alone is insufficient for meaningful adoption (Osrof et al., 2023).

5.3 Environmental Context

In the TOE model, environmental factors encompass regulatory frameworks, market structures, and broader socio-economic forces influencing adoption outcomes (Tornatzky et al., 1990). The findings highlight how Malaysia's paddy environment is characterized by extensive input subsidies, price controls on local rice, and a single dominant buyer structure (Bernas), which collectively reduce incentives for innovation. This observation aligns with Klerkx and Rose (2020), who emphasize the importance of stakeholders pursuing interventions or transitions that generate more beneficiaries than losers in adopting SFTs. Consequently, interventions designed to stabilize production can inadvertently discourage farmers from exploring advanced technologies. Furthermore, the absence of strong market-driven demand for premium or traceable rice results in farmers having minimal motivation to shift away from traditional practices. This scenario leads to a "policy lock-in," where existing subsidies ensure farmers' survival but fail to stimulate modernization. Additionally, fragmentation within the supply chain further complicates traceability efforts. Paddy from numerous smallholders is blended at milling

facilities, rendering it impractical to segregate or uniquely brand produce from individual farms. Broader environmental constraints, such as infrastructural and connectivity limitations, also significantly hinder digital data collection efforts. Limited internet access, unreliable electricity supply, and a shortage of technical experts in rural regions mean that the necessary external support systems for successful SFTs adoption are insufficient (Osrof et al., 2023). Overall, these issues mirror those of Kamilaris et al. (2019), who highlighted that a successful adoption of SFTs such as blockchain hinges on addressing multiple challenges, including accessibility, governance, technical competencies, and appropriate regulatory frameworks.

5.4 Implications for Research

The findings underscore the value of integrative theoretical lenses, specifically, Grounded Theory (Glaser & Strauss, 2017) combined with the Technology-Organization-Environment (TOE) framework (Tornatzky et al., 1990), for examining SFTs adoption in a complex, smallholder-driven context. Although many technology-adoption models exist, future studies can benefit from a stronger emphasis on local agronomic conditions and micro-level socio-economic factors, which emerged as critical drivers of SFTs adoption (Osrof et al., 2023). For instance, examining how plot fragmentation and off-farm employment influence technology-use intentions can deepen our understanding of adoption pathways in developing-country agriculture (Diana et al., 2024; FAO, 2022).

Moreover, cross-case comparisons, contrasting the paddy sector with other staple-crop systems in Southeast Asia, could illuminate whether the same barriers (e.g., cost and policy inertia) appear in different contexts. Researchers might also explore mixed-methods designs, incorporating quantitative measures (e.g., yield impacts, cost–benefit analyses) alongside qualitative insights, to triangulate findings and strengthen the generalizability of grounded conclusions (Creswell & Creswell, 2017; Guest et al., 2006). Finally, the role of service providers in mediating technology uptake deserves additional attention (Anastasiou et al., 2023). Although outsourcing mechanized tasks can reduce farmers' immediate capital outlays, it may also marginalize farmer skill development and diminish the perceived need for technology investments. Investigating how partnerships or cooperative models influence long-term learning and adoption patterns could generate fresh theoretical insights into service-driven SFTs deployment.

5.5 Implications for Practice

Facilitating SFTs adoption in Malaysia's paddy industry requires comprehensive policy reforms that move beyond traditional input subsidies and price controls (Klerkx & Rose, 2020). While these existing measures have stabilized farmer incomes, they inadvertently discourage the pursuit of advanced and potentially more profitable farming methods. Policymakers could introduce targeted incentive schemes, such as partial subsidies or tax relief specifically tied to the adoption of drones, sensor networks, and blockchain-enabled traceability systems. These incentives can be implemented through existing agricultural support programmes and aligned with national strategies such as the National Agro-Food Policy (NAP 2.0), ensuring that public funding directly supports the transition toward smart farming initiatives (MAFS, 2021).

Alongside financial incentives, strengthening extension services and digital literacy are equally urgent priorities. Aging smallholder farmers often lack the technological familiarity needed to operate drones or interpret sensor data, and are therefore resistant to investing time and resources in new tools (Diana et al., 2024; Dibbern et al., 2024). To address this, structured training programmes can be delivered through agencies such as IADA, MADA, and MARDI, incorporating hands-on demonstration farms, peer-learning sessions, and mobile-based training modules. These approaches can help translate abstract technological concepts into practical benefits. Additionally, concerted efforts to improve rural internet connectivity and infrastructure would facilitate the operation of SFTs and encourage farmers to embrace them to see tangible results, such as reduced labor costs and optimized resource use (Ahmad

et al., 2024; Osrof et al., 2023).

Addressing supply chain fragmentation is another essential step in unlocking the potential of advanced technologies. Currently, small landholders operate on scattered plots, central mills blend outputs from various farms, and most supply-chain actors lack digitized records, reducing the effectiveness of traceability solutions like blockchain (Tan et al., 2023). Encouraging collaborative models, such as farmer cooperatives, could consolidate land holdings and pool financial resources, thus lowering individual risks. Additionally, policies that mandate or incentivize digital record-keeping at every stage can foster more transparent and integrated tracking systems. Such unified data structures can support local quality assurance initiatives and broader commercial opportunities, including premium branding and export certification (Tan et al., 2023; Xu et al., 2020).

Finally, service providers play an increasingly pivotal role by offering on-demand mechanized tasks, from drone spraying to harvesting (Anastasiou et al., 2023). However, their capacity to invest in advanced equipment depends on the market's demand for those services. Policymakers could introduce co-investment schemes, low-interest technology upgrade loans, or equipment-sharing platforms to reduce financial risks. Incentives such as tech-upgrade loans or co-investment schemes could mitigate their financial risks and, in doing so, ensure that farmers gain access to higher-end technologies without bearing the initial capital costs themselves (Pedersen et al., 2024). Additionally, involving service providers in extension activities, where they can showcase cutting-edge machinery, helps create a knowledge-sharing network, fostering a technologically skilled ecosystem capable of rapidly scaling innovations.

6. Conclusion

This study highlights how SFTs adoption, including blockchain, drones, and sensors, encounters multi-layered constraints within Malaysia's paddy sector. Drawing on in-depth qualitative interviews and interpreting the findings through the TOE framework, eight core challenges emerged: high costs, older demographics, fragmented landholdings, technological mismatch, low digital literacy, policy misalignment, service-provider limitations, and a lack of end-to-end supply chain integration. These barriers are mutually reinforcing, shaped by smallholder risk aversion, infrastructural gaps, and policy structures, focusing primarily on production stability rather than embracing new innovations.

Against this backdrop, integrating Grounded Theory and the TOE framework provides nuanced insights about SFTs adoption from various stakeholders, going beyond previous studies that predominantly focused on quantitative research and farmers' perspective (Osrof et al., 2023). This research emphasizes the necessity of context-specific strategies by highlighting how specific local conditions, such as older farmer demographics and fragmented landholdings, intersect with broader environmental and policy dynamics (FAO, 2022; MAFS, 2021). Future technological developments must be carefully tailored to local agricultural conditions, and policy interventions should transition from input-centric subsidies to comprehensive incentives that promote innovation. In parallel, expanded extension services and digital-literacy programs are pivotal for fostering trust and competence in using these emerging tools.

Ultimately, such transformations can help Malaysia's paddy sector effectively leverage SFTs to enhance productivity, sustainability, and supply chain transparency, contributing significantly to national food security and rural development goals.

Notwithstanding its contributions, this study has several limitations. The perspectives of farmers were captured indirectly through agencies and related stakeholders rather than through direct engagement with farmers themselves. While this approach provides valuable ecosystem-level insights, it may not fully reflect first-hand farmer experiences, particularly in regards to attitudes, digital literacy, and risk aversion. Future research is therefore encouraged to incorporate primary data collection involving farmers to validate and extend these findings,

thereby enhancing the robustness and contextual accuracy of the conclusions. Although widespread adoption presents ongoing challenges, this study offers policymakers, agribusinesses, and researchers a targeted roadmap toward meaningful and inclusive agricultural advancement.

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Appendix A: Barriers Themes with Selected Quotes from Interviewees.

Barrier Theme	Bernas (B)	IADA Perak (P)	MADA Kedah (M)	IADA Penang (I)	MARDI Penang (R)
1. High Cost & Limited Economic Returns	▪ "Farmers basically don't get more. We get a better yield and reduce cost, so our side gains. But for them, it's the same price." ▪ "The margin for local paddy is tight… if the system is too costly, it won't pay off for smaller mills."	▪ "If you only have two hectares, you might get around MYR8,000 in a season… They can't invest in drones or other expensive tech." ▪ "At the end of the day, cost is key. If technology is cheap or it saves them money, they'll try. Otherwise, they won't."	▪ "On average, maybe two hectares yield only about MYR2,300 monthly if you break it down… not that much." ▪ "The subsidy is crucial but only helps them continue the same routine. There's no push for advanced technology."	▪ "Any new technology we are bringing is not equivalent with the cost that farmers have to pay… farmers cannot afford to pay the technology." ▪ "We want to promote a new machine… but it's too expensive, the farmer can't get back the investment."	▪ "They don't want to invest more on technology. So, it's all about economic perspective: cost and yield." ▪ "We cannot 100% guarantee it will increase yield… The only sure thing is reducing cost and maintaining yield."
2. Older Farmer Demographics & Risk Aversion	▪ (No direct age-specific quotes, but mentions farmers not incentivized to adopt.)	▪ "We see many owners are 70 or 80 years old… old folks prefer safer, cheaper methods." ▪ "They worry if they try new machines, the yield might drop… then they lose one entire season's income."	▪ "We have about 54,886 farmers; the average age is around 60. Under 30 is only 1.9%. Many are over 70—24%." ▪ "Inheritance issues… some even 100 years old are still the official owner."	▪ "95% are very old farmers… it's not easy for them to change their mind." ▪ "Young farmer usually more open… but their involvement remains limited."	▪ "70% is 45 and above. So, it's hard to get them involved in these technologies."

Barrier Theme	Bernas (B)	IADA Perak (P)	MADA Kedah (M)	IADA Penang (I)	MARDI Penang (R)
3. Small / Fragmented Landholdings & Part-Time Farming	▪ "We cannot see which farmer's paddy goes into which final bag… We just combine them… so we can't track 'which farm did this rice come from.'" (Indirectly noting many small farms converge at the mill.)	▪ "The average farmer only has 3 acres… tough for them to buy big machines." ▪ "We open tender for laser leveling, but few operators. Many small plots remain not serviced."	▪ "Our average farmland size is about 2.02 hectares each, but many own less than 0.5." ▪ "Only 3.7% have more than 6 hectares. So large-scale operations are not the norm."	▪ "75% are part-time farmers… 1–2 hectares only. They cannot survive if they only do paddy." ▪ "We target 5 hectares minimum for a full-time farmer… but it's very hard because land is limited."	▪ "Almost 70% is a small individual farmers." ▪ "The average farmer's age is 45 and above… so combined with small plots, it's slow to adopt new technologies."
4. Technological Mismatch & Infrastructure Gaps	▪ "It's hard to segregate paddy from each farmer… we also can't do high-tech scanning for every truck." ▪ "Some advanced systems are too costly for smaller mills."	▪ "We only have one month for land prep… operators can't cover everyone in that narrow window." ▪ "Drones are simpler, but bigger machinery that needs uniform blocks can't do well on scattered small plots."	▪ "If using a transplanter, the field must be just wet… but some areas have continuous water… Hard to adopt the machine." ▪ "We do land leveling, but not all places."	▪ "Big harvesters are too heavy for our waterlogged soil, so we switched to smaller harvesters." ▪ "Sometimes that technology is good for another area but not ours. Suitability is an issue."	▪ "Agriculture is the least sector to embrace IR4.0… we don't have digital baselines. We also lack uniform fields… The machines need uniformity to implement it better." ▪ "Internet connectivity in rural areas is also a challenge."
5. Low Digital Literacy & Limited Training	▪ "Even with our new APD (Automated Paddy Dryer), staff still do final checks manually. Data entry ends up in spreadsheets." (Indicating partial digital adoption but	▪ "Farmers themselves don't know about IoT systems… we might do pilot tests in a small block, but large-scale adoption is still far off."	▪ "Farmers do not generally use digital systems—there's no app or platform for them." ▪ "We have IR4.0 in one pilot area, but they still rely on service	▪ "We have extension programs, but out of 700 farmers, only 30–50 come." ▪ "They're busy or part-time… so they skip the training. It's not enough."	▪ "If they don't have, at least, a diploma, it's hard for them to understand how to do this work [with advanced tech]." ▪ "We also need more experts… it's quite complicated to

Barrier Theme	Bernas (B)	IADA Perak (P)	MADA Kedah (M)	IADA Penang (I)	MARDI Penang (R)
	persistent legacy habits.)		providers… not direct usage by farmers."		handle the technology or the data."
6. Policy & Institutional Barriers	▪ "We have Denali (ERP) for internal records… but it doesn't link with farmers or the packaging side. The supply chain is fragmented." ▪ "Our local rice price is controlled… we can't just brand it as premium."	▪ "We rely on a yearly budget for drone spraying or laser leveling… next year we might have less. That's how we do it, by tender." ▪ "We don't give machinery grants for big or advanced equipment."	▪ "We have 27 PPK… each organizes land differently, so farmers get confused. Some prefer to do everything themselves." ▪ "Subsidies are crucial but they just keep the same routine."	▪ "Our extension programs focus on cost reduction and enhance farming practices, not about blockchain or complicated systems." ▪ "If we don't have subsidies, farmers cannot survive… but they don't cover big technology investment."	▪ "Sometimes it depends on RMK cycles. This year we focus on pineapples, next year maybe rice… no continuity for big digital transformations." ▪ "No single body regulates agri-machineries (like PUSPAKOM for vehicles). We proposed a 'Machineries Testing Center.'"
7. Service Provider / Operational Constraints	▪ "When a truck arrives, we do sampling. It's all manual. If it's a 20% cut, the farmer may negotiate."(Bernas relies on staff to handle intake; no direct mention of on-farm service providers, but they note that farms do not handle these processes themselves.)	▪ "Only a few private operators do laser leveling… they can't finish the entire area in the short planting window." ▪ "Farmers rely on the Brigade Tani or private operators for pesticide/fertilizer spraying."	▪ "About 70% farm individually, 30% do estate management with the PPK… but not everyone trusts the PPK. Some want to do it themselves." ▪ "We have service providers for harvest, but even then, not all adopt new machines."	▪ "In paddy area, not just the farmers… They must have a service provider for plowing, spraying, harvesting." ▪ "Part-timers rely almost entirely on outside machinery operators."	▪ "Smallholders mostly outsource advanced operations to service providers. They themselves do not directly adopt it… so the technology might not fully transfer knowledge to the farmer."

Barrier Theme	Bernas (B)	IADA Perak (P)	MADA Kedah (M)	IADA Penang (I)	MARDI Penang (R)
8. Lack of Supply Chain Integration & Data for Traceability	▪ "It's hard to segregate paddy from each farmer… we blend for big batches, so we can't track farm-level origins." ▪ " To use blockchain or advanced traceability, we should isolate each farm's paddy. That's not how we run the mill."	▪ "The farmer's job ends once they sell to the mill… yield data is just basic weighing. No one logs it into an integrated system." ▪ "If there's a blockchain idea, we'd need consistent data from each plot. Hard to do when everything is so scattered."	▪ "Farmers don't share digital data… The mill does weigh checks, minus quality. That's it." ▪ "There's no big data or integrated system from farm to mill. So full traceability is difficult."	▪ "Farmers are not aware of these advanced technologies… we are at the early stage. They don't know about it." ▪ "Our focus is cost reduction. Traceability or blockchain is not on the ground yet."	▪ "For rice, it's quite complicated… seed producers, service providers, mills, etc. We don't have a single chain-of-custody platform." ▪ "We lack baseline digital data, so a true farm-to-fork blockchain is mostly theoretical right now."