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Between Tradition and Technology: A Comparative Framework for Context-Sensitive Agricultural Innovation in Malaysian Rice Systems

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ABSTRACT

The agricultural sector is facing substantial transformation driven by the combined pressures of climate variability, resource degradation, and unstable markets. Addressing these challenges requires solutions that are technologically advanced yet firmly grounded in real-world contexts. Integrating modern tools with traditional knowledge provides opportunities to enhance productivity, safeguard ecosystems, and secure the long-term stability of food supplies. Drawing on two contrasting Malaysian rice-sector case studies namely a precision-agriculture intervention and the persistence of traditional Iban rice cultivation, this paper develops a case-based conceptual framework for evaluating when agricultural innovation is adopted and sustained. This paper reflects on how innovation in farming can be aligned with broader sustainability goals by bringing together technological, ecological, and socio-economic perspectives. The discussion highlights that progress is most meaningful when approaches fit local realities, drawing on community values and environmental knowledge while also responding to global pressures. Framing agriculture at the crossroads of tradition and modern methods shows that transformation is not just about yields, but also about protecting biodiversity, sustaining cultural practices, and supporting fairer forms of development. The findings indicate that advances in farming are most effective when they remain accessible, affordable, and inclusive for all communities. The paper's specific contribution is to show that cultural relevance and ecological sensitivity operate jointly, rather than separately, as the conditions under which agricultural innovation endures. Achieving this outcome requires supportive policy frameworks, institutional collaboration, sustained investment in knowledge-sharing and capacity building. Stronger partnerships between governments, research institutions, and farmers are essential to ensure that innovations are implemented effectively and equitably. When these elements in place, agricultural change can deliver more than immediate gains. It can also contribute to stronger communities, healthier ecosystems, and food systems capable of enduring future challenges.

Keywords: Tradition, agricultural challenges, innovation, agricultural advancement

INTRODUCTION

Agriculture in Malaysia is increasingly shaped by the need to balance traditional practices with technological innovation. On one side, farming systems carry deep cultural, ecological, and Indigenous significance, rooted in generations of knowledge and adaptation. On the other hand, modern technologies promise gains in productivity, efficiency, and competitiveness that are essential for meeting national food security goals. The intersection of these two dimensions of tradition and technology defines both the challenges and the opportunities for agricultural transformation. The Food and Agriculture Organization (FAO) characterized of Indigenous agriculture as the food and knowledge systems built on practices such as shifting cultivation, agroforestry, seed saving, and ritual planting cycles, through which Indigenous communities pursue a holistic approach to food production, biodiversity conservation, and cultural continuity (FAO).

In this paper, the term is used specifically to describe the rice-growing practices of the Iban community in Sarawak's Batang Lupar, and more broadly to refer to smallholder systems in which farming decisions remain embedded in kinship, ritual, and place-based ecological knowledge, as distinct from estate-based or fully commercialized production. From an economic perspective, farming remains under pressure from high input costs, fluctuating commodity prices, and growing dependence on subsidies (Dorairaj & Govender, 2023). Fertilizer, seed, and mechanization support form a substantial share of farm profitability, and without these measures, many small and medium farmers would struggle to remain viable. At the same time, international competition from regional exporters highlights structural vulnerabilities, exposing the risk that domestic agriculture could be undermined if support mechanisms are withdrawn. This financial fragility makes the careful integration of efficiency-enhancing innovations a pressing necessity.

Beyond economics, agriculture in Malaysia is embedded in cultural and ecological contexts. Traditional systems provide resilience through local adaptation, seed diversity, and community-based practices that sustain livelihoods and safeguard heritage (Altieri & Koohafkan, 2008). For Indigenous farmers in particular, agriculture is not only an economic pursuit but also a cultural practice tied to rituals, identity, and stewardship of natural resources. These values offer lessons in sustainability that complement modern approaches to intensification. At the same time, technological innovation—including digital tools, precision agriculture, and improved crop management—provides opportunities to optimize input use, reduce waste, and increase yields. Yet the success of these technologies depends on accessibility and cultural relevance. When innovations are adapted to local realities, such as through cooperative service models or practices that mirror traditional knowledge, adoption is more likely (Rahim *et al.*, 2021). When technologies are imposed without sensitivity to context, however, they risk exclusion, low uptake, or even conflict with established cultural norms. The balance between food security and food sovereignty further illustrates the importance of context.

Efforts to raise self-sufficiency ratios have traditionally emphasized yield and output, but this narrow focus can overlook the broader contributions of traditional systems to resilience, biodiversity, and household security. Recognizing the complementary roles of both traditional and modern approaches allows agricultural development to move beyond a single metric of productivity towards a more inclusive model of resilience and sustainability. These dynamics also carry important policy implications. Agricultural programs must be designed with heterogeneity in mind, addressing the needs of large-scale producers, smallholders, and Indigenous communities alike. Public research institutions play a critical role in bridging innovation with accessibility, ensuring that new tools are not only scientifically robust but also socially and culturally embedded. In this way, policy frameworks can help ensure that innovation supports equity, protects heritage, and enhances resilience alongside economic efficiency.

Methodological & framework

This paper adopts a case-based conceptual synthesis approach rather than a primary empirical study. It integrated empirical findings from two field-based case studies previously conducted and published by the corresponding author and collaborators: (1) a precision agriculture initiative at FELCRA Seberang Perak, evaluated a two-season cost benefit analysis of Variable Rate Technology (VRT) and Green Area Index (GAI) canopy modelling against conventional practice (Rahim *et al.*, 2021), and (2) an economic and varietal assessment comparing traditional Iban with modern commercial cultivars at at IADA Batang Lupar, Sarawak (Rahim *et al.*, 2022; Wahab *et al.*, 2025). These empirical cases are systematically cross-referenced with comparative literature on context-sensitive technology adoption from sub-Saharan Africa, South Asia and Latin America to ensure global relevance. It comes along together with supplementary literatures on cultural relevance, ecological sensitivity, and technology adoption. The two cases were selected because they anchor opposite ends of the tradition–technology dimensions: one represents a technology-anchored intervention in a commercial estate setting, while the other reflects a tradition-anchored practice persisting within a national food security policy framework.

Evaluating them together through the dual analytical lens of cultural relevance and ecological sensitivity (Figure 1) enables this study to examine how local socio-ecological contexts condition technology adoption, rather than treating adoption as a purely technical or economic outcome. Specifically, the paper is guided by two research questions: (1) Under what economic, cultural, and ecological conditions is an agricultural technology or practice successfully adopted and sustained across different scales of Malaysian farming (smallholder, estate-based and Indigenous)? and (2) How can traditional practices and technological innovation be systematically integrated, rather than treated as competing alternatives, to support agricultural transformation that is equitable, culturally grounded, and ecologically resilient? By addressing these questions, the paper moves beyond descriptive synthesis to articulate a structured evaluative framework for context-sensitive agricultural innovation.

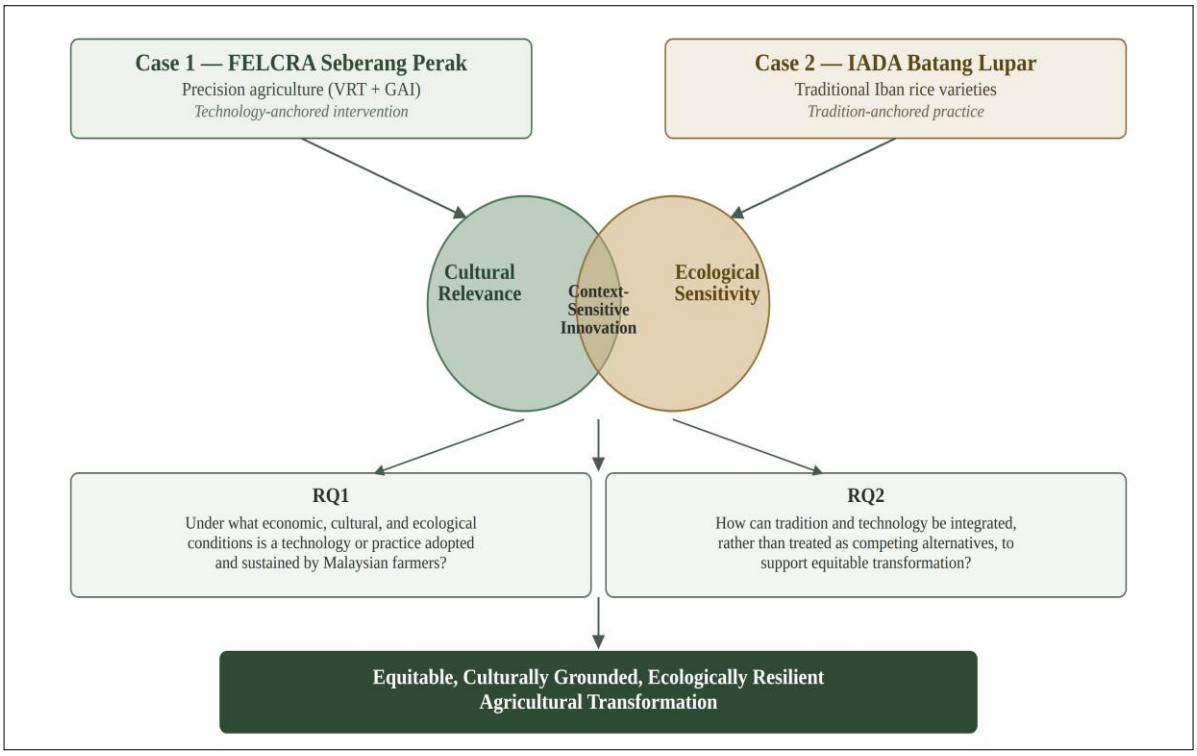


Figure 1. Two contrasting cases evaluated through cultural relevance and ecological sensitivity

As illustrated in Figure 1, this conceptual framework positions agricultural transformation at the intersection of cultural relevance and ecological sensitivity. Rather than treating tradition and modern technology as mutually exclusive choices, the framework evaluates how context-sensitive innovation emerges when technological efficiency is harmonized with local ecological boundaries and socio-cultural values. By applying this dual analytical lens to the contrasting cases of FELCRA Seberang Perak (technology-anchored) and IADA Batang Lupar (tradition-anchored), the following sections examine the specific economic, institutional and environmental conditions under which agricultural technologies are successfully adopted, sustained and integrated into national food security strategies.

THE IMPORTANCE OF CONTEXT-SENSITIVE AGRICULTURAL TECHNOLOGIES

Agricultural innovation cannot be understood solely in terms of technical efficiency or yield outcomes; its success depends on how well new tools align with local contexts. Technologies that ignore cultural practices, ecological conditions, and socio-economic realities often face low adoption rates or generate unintended consequences. In Malaysia, where rice farming occurs across diverse agro-ecological zones and among both commercial and Indigenous farmers, context sensitivity is particularly critical. From an economic perspective, context determines whether an innovation generates real benefits for farmers.

Precision agriculture at FELCRA Seberang Perak for instance, illustrates how cost-saving technologies such as variable-rate seeding and Green Area Index (GAI)-based fertilizer application can deliver higher profitability—raising net incomes by up to 44% compared to conventional methods—but only when introduced through shared service models that reduce entry barriers (Rahim *et al.*, 2021). Without such institutional arrangements, the capital requirements of advanced machinery would place them far beyond the reach of smallholders. In contrast, traditional rice varieties in Batang Lupar demonstrate economic resilience not through yield, but through high market value (RM4.20/kg) and low input costs, sustaining household income in ways that commercial rice cannot always match (Rahim *et al.*, 2022).

These examples confirm that technologies must be adapted to both farm-scale economics and local market dynamics. Context also shapes the cultural and social relevance of agricultural technologies. Another case, the indigenous Iban farmers in Batang Lupar, rice cultivation is more than a production activity—it is a cultural practice tied to rituals, identity, and food sovereignty (Wahab *et al.*, 2024). Technologies that displace these values risk alienating communities and eroding cultural heritage. Conversely, innovations that reflect traditional knowledge such as GAI-based canopy observation, which parallels indigenous methods of visually assessing crop

health. It may contribute to greater acceptance by making new tools more familiar and complementary to existing practices although this relationship requires empirical validation.can enhance adoption by making new tools feel intuitive and complementary to existing practices. This illustrates how the integration of traditional ecological knowledge with modern technologies can build trust and strengthen uptake.

The dimensions used in Table 1 build on the established literature on enabling factors and barriers to agricultural technology adoption among smallholder farmers, which identifies agro-ecological suitability, institutional support, financial constraints, and infrastructure access as recurring determinants of adoption outcomes (Rurii & Muasya Nzengya, 2026). Table 1 extends this framework by foregrounding cultural relevance and ecological fit specifically, rather than treating them as generic "social" or "environmental" barriers, and by showing how the same determinants combine differently for estate-based, smallholder, and Indigenous producers. Similar tensions between standardized-technology adoption and context-specific barriers have been documented among smallholders in sub-Saharan Africa (Rurii & Muasya Nzengya, 2026) and in traditional seed systems in South Asia (Sannegowda & Garkoti, 2022), suggesting the Malaysian pattern described here is not unique to Southeast Asia.

Table 1. Comparison of context-sensitive and non-context-sensitive agricultural technologies

Dimension	**Context-sensitive technologies**	**Technologies with limited context adaptation**
Economic Outcomes	Aligned with farm size, local markets; ensures profitability (e.g., MRQ rice niche markets, FELCRA service models)	Often unprofitable for smallholders; high dependency on subsidies
Adoption by Farmers	High adoption when adapted to local realities (shared services, intuitive methods)	Low adoption due to high cost or mismatch with local practices
Cultural Relevance	Integrated with traditions and Indigenous knowledge (e.g., canopy observation practices)	Risk of displacing cultural heritage and eroding farmer trust
Environmental Fit	Adapted to local ecosystems; supports resilience to climate variability	May cause environmental stress when imposed in unsuitable zones
Policy Implications	Requires flexible, plural policies that recognize heterogeneity among farmers	Standardized policies risk marginalizing Indigenous and smallholder farmers

The environmental dimension further underscores the importance of context. Traditional rice varieties grown in tidal wetlands and coastal rice systems are often lower yielding than modern commercial cultivars. However, they possess ecological adaptations to recurrent flooding, submergence and salinity stress in certain environments, making them valuable for improving climate resilience under changing environmental conditions (Khairullah *et al.*, 2025; Khairullah *et al.*, 2023; Senapati & Behera, 2026; Muralikrishnan *et al.*, 2021; Adinata *et al.*, 2025; Simarmata *et al.*, 2021). In contrast, high-yielding commercial varieties generally perform best when supported by sufficient inputs and grown under suitable environmental conditions. However, varietal mismatch in flood-prone, acid sulfate soil, or saline environments may reduce crop adaptation, yield stability, and overall productivity (Khairullah *et al.*, 2023; Lestari *et al.*, 2020; Ratmini & Herwenita, 2021).

Similarly, precision farming in FELCRA aligns with Malaysia's sustainability agenda by minimizing nitrogen runoff and promoting balanced soil nutrition, consistent with broader evidence that variable-rate/precision nitrogen management can reduce nitrate leaching, though outcomes vary by system and site (Ruder *et al.*, 2026). In both cases, the technologies succeed not simply because they are advanced, but because they are matched to ecological conditions and environmental goals. It should be noted that standardized technologies are not inherently unsuccessful: commercial high-yielding rice varieties in comparable Malaysian granary schemes such as IADA Kota Belud have achieved substantially higher yields (~2.9 mt/ha) than traditional varieties even without localized cultural adaptation, where strong subsidy, extension, and infrastructure support were in place (Rahim *et al.*, 2022). This suggests that the outcomes summarized in Table 1 depend as much on the strength of

enabling institutions as on cultural or ecological fit per se, a point developed further in the Batang Lupar case below.

Finally, context sensitivity carries significant policy implications. Standardized subsidy programs that treat all farmers alike may unintentionally favor large-scale commercial systems while marginalizing smallholders and Indigenous producers. Instead, agricultural policies should recognize heterogeneity, supporting plural strategies: mechanization and precision tools in large estates, niche-market support for traditional varieties in Indigenous communities, and hybrid approaches where both coexist. Public institutions such as the Malaysian Agricultural Research and Development Institute (MARDI) play a critical role in bridging these approaches, designing technologies that are not only efficient but also culturally appropriate, environmentally sound, and economically inclusive. Context-sensitive agricultural technologies are essential for ensuring that innovation contributes to equity, resilience, and sustainability. Malaysia's experiences at FELCRA Seberang Perak and Batang Lupar demonstrate that when technologies are tailored to local realities, they generate broad benefits in terms of economic viability, cultural relevance, and ecological resilience. When divorced from context, even the most sophisticated tools risk would have limited impact.

Recognizing and embedding context sensitivity into agricultural research, extension, and policy design is therefore a cornerstone of sustainable rural transformation. Agricultural innovation is not simply a technical exercise; it is deeply embedded within the cultural fabric of societies. Technologies that align with local values, traditions, and social norms are more likely to be accepted, sustainable, and effective. Traditional agricultural knowledge, including rituals, beliefs, and oral practices, supports community identity and guides environmental management (Wan Talaat, Mohd Tahir, & Husain, 2012). This citation specifically concerns Terengganu coastal communities' traditional practices for cultivating and safeguarding genetic resources, including seed selection, saving, and exchange; whether this particular practice measurably enhances farmers' adaptive capacity, as distinct from sustaining cultural continuity, has not been directly tested in the cited source and is flagged here as a question for future empirical work. Rice cultivation among the Iban of Sarawak and the Kadazan-Dusun of Sabah combines technical knowledge with ritual cycles that maintain spiritual ties to the land and serve as ecological calendars (Ab. Halim, Othman, Ismail, Jawan, & Ibrahim, 2012). The significance of cultural relevance is further underscored in the way communities adapt to climate challenges through belief systems and practices. Island communities in Terengganu, Malaysia, have demonstrated that traditions strengthen resilience, economic stability, and social cohesion (Samsuddin, Salleh, Talaat, & Saputra, 2024).

Such evidence highlights that resilience cannot be understood solely in technical terms, but must be seen as rooted in social cohesion and cultural preservation. At the global level, cultural relevance is recognized as essential for biodiversity conservation under the Convention on Biological Diversity. In line with this, agricultural education initiatives stress the importance of integrating indigenous knowledge systems into curricula to ensure that sustainability is taught in ways that resonate with the cultural realities of local communities (Williams & Muchena, 1991). Embedding cultural relevance into agricultural policy also plays a vital role in bridging generational knowledge gaps. Mahmud (2025) stresses that incorporating traditional ecological knowledge (TEK) into climate change education equips younger generations with culturally grounded strategies for resilience. Similarly, Adefila, Ajayi, Toromade, and Sam-Bulya (2024) argue that integrating traditional knowledge with modern agricultural practices within sociocultural frameworks fosters innovation without eroding identity.

In this regard, cultural relevance in agricultural technologies extends far beyond mere acceptance. It safeguards identity, empowers marginalized voices, and ensures the continuity of living knowledge systems. Without this dimension, technological interventions risk alienating communities, eroding trust, and ultimately failing to deliver on sustainability goals. Ecological sensitivity underscores the need for agricultural technologies to align with the ecological realities of specific environments. It acknowledges that ecosystems are diverse, fragile, and shaped by centuries of human–nature interaction. Technologies that disregard this sensitivity often degrade resources (Tilman, Cassman, Matson, Naylor, & Polasky, 2002), while those that draw upon ecological wisdom contribute to long-term sustainability. Indigenous agricultural practices provide powerful examples of ecological sensitivity. Rotational farming and mixed cropping in Sabah, for instance, help conserve biodiversity and maintain soil fertility, countering the ecological damage of monocropping and industrialized farming systems (Ab. Halim *et al.*, 2012).

Similarly, conserving traditional agriculture as a living knowledge system, rather than reducing it to a cultural relic which supports resilience by maintaining genetic diversity, landscape health, and ecological functions essential for stability (Nazarea, 2006). Research shows that TEK provides fine-grained ecological insights that are often overlooked by modern science. Local seed varieties, cultivated and conserved through community-led traditional seed systems including farmer-to-farmer exchange and on-farm selection for local

stress tolerance in which offer adaptive strategies against pests, droughts, and soil degradation (Sannegowda & Garkoti, 2022). Such practices preserve agro-biodiversity, which is a crucial buffer against climate shocks. The urgency of ecological sensitivity is heightened under climate change. Malaysia faces rising temperatures, irregular rainfall, and recurrent floods, all of which threaten agricultural productivity and rural livelihoods (Mahmud, 2025). In such contexts, TEK such as water harvesting, soil conservation, and agroforestry offers tested, ecologically sound methods for managing variability.

Island communities in Malaysia further illustrate how adaptive practices rooted in tradition sustain both ecosystems and livelihoods under increasing climate pressures (Samsuddin *et al.*, 2024). Educational and policy strategies for sustainable agriculture must integrate ecological sensitivity alongside scientific and indigenous practices (Williams & Muchena, 1991; Rahim & Sabri, 2023). Hybrid models that combine ecological and cultural knowledge with modern technologies, including geographical indicators and indigenous branding, support environmental stewardship, economic sustainability, and resilience (Adefila *et al.*, 2024; Nazarea, 2006). In essence, ecological sensitivity and cultural relevance together form the foundation of context-sensitive agricultural technologies. Cultural alignment ensures innovations respect community identity and traditions, while ecological sensitivity preserves fragile ecosystems. Together, they foster sustainable, equitable, and resilient food systems. While the integration of cultural relevance and ecological sensitivity provides a strong foundation, several challenges remain when translating these ideas into practice.

One of the main issues is that the involvement of local communities in shaping technologies is often more symbolic than genuine. Decisions are still largely guided by external actors, and local voices do not always influence the design or direction of innovations. This weakens the sense of ownership and limits the long-term sustainability of initiatives. Another challenge lies in balancing environmental stewardship with the pursuit of economic growth. Although ecological approaches have shown success in conserving biodiversity and supporting community livelihoods, they are frequently undermined by development pressures and short-term policy priorities. This creates a tension where conservation goals are acknowledged but not fully protected in practice, leaving ecosystems vulnerable to degradation. Climate-focused innovations also face uneven outcomes. Advanced technologies can support adaptation but are often inaccessible to smallholders, while traditional practices, though effective, remain under-recognized.

Poor integration of scientific advances with community knowledge and unequal distribution of post-harvest improvements limit their impact. Market barriers, weak institutions, and profit-driven priorities further constrain benefits, preventing innovations from fully reducing losses, strengthening food systems, and preserving cultural identity. Taken together, these challenges suggest that the future of agricultural innovation depends not only on developing new tools and practices but also on creating structures that ensure inclusivity, equity, and long-term ecological balance. Without such changes, even the most promising innovations risk losing continuity with the very communities and ecosystems they are intended to support. These reflections highlight that while progress has been made, the path forward requires closer attention to how innovations are shaped, shared, and sustained a consideration that leads directly to the focus on key areas of research.

SHAPING THE FUTURE OF AGRICULTURE

Recognizing these challenges makes it clear that future progress depends on focused inquiry, which can be guided by several key areas of research. Building upon the need for agricultural technologies that are both culturally relevant and ecologically sensitive, several areas of research stand out as particularly important for guiding sustainable innovation. These areas not only address present challenges but also provide pathways for long-term resilience and equity in agricultural systems. First, strengthening community involvement is crucial. Farmers must be more than just recipients of new technologies; they need to be active participants in shaping and adapting them. Research into collaborative approaches can help ensure that knowledge flows both ways, blending scientific advances with the practical wisdom of local communities. Such approaches enhance trust, increase adoption, and protect cultural heritage.

Second, greater attention to ecosystems is required. Agriculture cannot be separated from the landscapes in which it takes place. Studies that link biodiversity, soil health, water management, and crop productivity reveal the potential of ecosystem-based strategies to sustain yields while maintaining ecological balance. These approaches are especially valuable in areas facing intense environmental pressure, where the health of ecosystems directly determines the security of livelihoods. Third, adapting to climate variability has become a central priority. With agriculture among the sectors most vulnerable to climate change, research into resilient practices and technologies is urgently needed. This includes exploring both advanced tools and traditional adaptive knowledge

to create strategies that are affordable, inclusive, and effective in diverse contexts. Climate resilience research ensures that farming communities are equipped to withstand shocks and maintain productivity.

Finally, improving post-harvest systems and value addition offers opportunities to reduce losses and enhance livelihoods. Research in this area explores how innovations in storage, processing, and marketing can preserve food quality and open new markets. When designed with sensitivity to culture and ecology, these innovations can extend benefits beyond economics, reinforcing local identity and promoting sustainability along the value chain. Taken together, these research areas reflect the central idea that sustainable agricultural innovation is not about choosing between tradition and modernity, but about weaving them together into practices that are adaptive, inclusive, and resilient.

Participatory models for Indigenous agriculture

Collaborative farmer–researcher approaches treat farmers, including Indigenous and rural communities, as equal partners in agricultural research. By blending local knowledge with scientific insights, these methods produce innovations that are practical, sustainable, and culturally grounded. Farmers are seen not as passive recipients of technology but as innovators whose lived experiences contribute to shared learning, open dialogue and mutual decision-making (Lavandero *et al.*, 2025). Traditional practices and ecological knowledge are integrated into agricultural development, ensuring respectful and inclusive processes.

Collaborative experimentation and adaptation encourage interactive learning among farmers, researchers, and extension agents, allowing solutions to be tailored to the local context (Vidyawati *et al.*, 2025). Involving farmers from the earliest stages—identifying problems through to testing and refining solutions—can increase the adoption of sustainable practices. Participatory methods such as plant breeding (Swiderska *et al.*, 2018) and soil fertility management (Wadoux & McBratney, 2023) encourage interactive learning and context-specific solutions. Community-led research groups go further, allowing farmers to set their own agendas and adapt innovations over time (Hoffman *et al.*, 2007; Ashby *et al.*, 1995). These models build ownership, confidence, and a culture of collaboration.

In Indigenous contexts, combining participatory and community-led approaches enhances respect for cultural traditions and self-governance. As agricultural systems evolve, digital innovations such as mobile advisory apps, remote sensing, and smart irrigation systems are increasingly being added to these participatory frameworks. These tools can help Indigenous farmers manage climate risks, make informed decisions, and use resources more efficiently. For example, IoT-enabled irrigation systems can monitor soil moisture and supply water when it is needed, while mobile apps can give real-time advice on weather, pests, and planting schedules (Klerkx *et al.*, 2019). However, for digital tools to be effective, they must be co-designed with the communities that will use them, taking into account local knowledge, cultural practices, and environmental conditions. Despite their potential, the adoption of digital tools among Indigenous farmers is still limited. Barriers include poor internet connectivity, lack of access to smartphones, and different levels of digital literacy. Technologies that are not designed in the local language or that fail to fit with cultural norms may seem irrelevant, while inadequate training and lack of ongoing support further limit long-term use (Eastwood *et al.*, 2019).

These participatory and digital approaches also face structural constraints beyond individual technology design. Institutional inertia within research and extension agencies can limit how much decision-making authority is genuinely transferred to farmers, so that participation remains consultative rather than agenda-setting (Klerkx *et al.*, 2019). Funding for participatory research is often project-based and short-term, which constrains the multi-year engagement that trust-building with Indigenous communities requires, while digital-literacy gaps compound these constraints by concentrating the benefits of new tools among better-resourced households, and raising ongoing maintenance and training costs that are rarely budgeted for beyond the initial rollout (Eastwood *et al.*, 2019). Without addressing these institutional and financial barriers directly, participatory and digital approaches risk becoming symbolic rather than substantively empowering.

Designing digital innovations that are context-sensitive and inclusive requires integrating collaborative farmer–researcher approaches and community-led research groups. Early farmer involvement through feedback, local testing, and co-design workshops enhances usability, cultural relevance, and long-term adoption. For example, mobile apps co-developed with communities improve accessibility (Steinke *et al.*, 2022), while IoT systems tailored to local cropping cycles ensure practical application (Kumar *et al.*, 2020). Digital tools built on principles of equity, empowerment, and mutual respect are more likely to be adopted and sustained. The participatory approaches discussed above vary in their technological complexity, knowledge requirements, and

suitability for different Indigenous and smallholder farming contexts. For easier comparison, these approaches are summarized in Table 2, which highlights their core features, benefits, example applications, and potential adoption barriers.

Table 2. Summary of selected participatory agricultural approaches, their benefits, and common adoption barriers in Indigenous and smallholder contexts

Technology/approach	Key features	Benefits	Barriers/challenges
Participatory plant breeding	Farmers + breeders develop crop varieties	Locally adapted, climate-resilient crops	Requires training, long time to develop
Participatory soil fertility management	Combine traditional soil care + modern nutrient science	Improved soil health & sustainability	Knowledge transfer & farmer participation needed
Mobile advisory apps	Real-time advice on weather, pests, planting	Improved decision-making & risk reduction	Connectivity gaps, digital literacy issues
IoT-enabled irrigation	Soil moisture sensors & automated watering	Efficient water use, improved yields	Upfront costs, maintenance skills

Source: Adapted from Swiderska *et al.*, 2018; Wadoux & McBratney, 2023; Steinke *et al.*, 2020; Kumar *et al.*, 2020

Combining participatory research methods with digital innovation offers a strong path toward sustainable and resilient agricultural systems. Treating Indigenous farmers as equal collaborators ensures that tools and practices reflect their knowledge, priorities, and needs, thereby strengthening food sovereignty and long-term resilience to climate and social challenges. These approaches extend beyond productivity, contributing to environmental goals by aligning with ecosystem-based strategies that emphasize biodiversity and ecological balance. Embedding conservation values into agricultural technologies supports both socio-economic resilience and the protection of natural and cultural resources. This connection sets the stage for exploring how technology can be used to advance biodiversity protection and ecosystem-based management in Indigenous agriculture. While participatory technology development focuses on empowering communities to co-create solutions, sustaining agricultural livelihoods also depends on protecting the ecosystems they rely on. This leads to the next key pillar: ecosystem-based approaches that safeguard biodiversity while integrating technological innovation.

Ecosystem-based approaches and biodiversity protection through technology

For Indigenous communities, protecting biodiversity and healthy ecosystems is inseparable from cultural heritage and ecological knowledge. Rising threats such as land degradation, climate change, and unsustainable land use highlight the role of agricultural technologies in supporting ecosystem-based approaches that align with Indigenous stewardship principles. When adapted to local contexts, tools like GIS mapping, remote sensing, and biodiversity tracking can strengthen conservation efforts while promoting sustainable farming (Kpienbaareh *et al.*, 2020). Measurable indicators used in this literature include species diversity counts, soil organic matter content, and water-quality parameters, which provide concrete benchmarks against which the ecological outcomes of these technologies can be evaluated, rather than treating "biodiversity protection" as a general aspiration (Kpienbaareh *et al.*, 2020).

Ecosystem-based approaches in Indigenous agriculture focus on maintaining ecological balance, protecting soil health, preserving seed diversity, and ensuring the availability of clean water. These priorities match well with modern technological tools that deliver precise, real-time information on land use, vegetation cover, and biodiversity patterns. For example, GIS and drone-based aerial surveys have helped Indigenous groups map cultural heritage sites, track environmental changes, and maintain control over their lands especially when used alongside traditional land management practices (Ferreira & Delgado-Serrano, 2024). Remote sensing adds further value by detecting land use changes and identifying areas at risk from resource exploitation. This allows for more proactive and informed environmental decisions. When implemented with Indigenous participation,

these technologies not only improve environmental monitoring but also help protect customary land rights by producing credible evidence to support legal recognition and territorial claims (Danielsen *et al.*, 2022).

It is equally important that Indigenous communities maintain control over the data these tools produce, ensuring its use aligns with traditional governance systems and supports self-determination. Figure 2 illustrates how GIS, remote sensing, and related technologies are integrated into Indigenous agricultural systems from initial data collection through processing, practical applications, and the resulting community benefits.

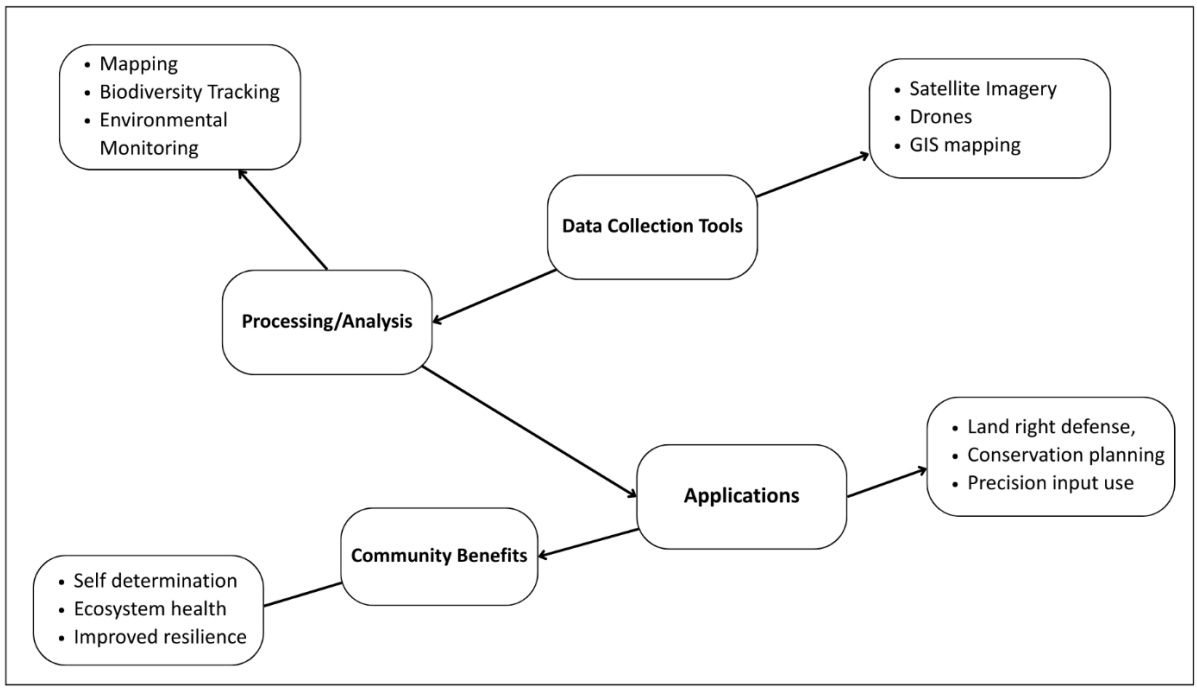


Figure 2. GIS and remote sensing integration pathway for Indigenous agriculture.

The effective use of agricultural technologies is also key to building a sector that is efficient, climate-resilient, and inclusive (Wah, 2024). Farmers in many regions face growing challenges from climate variability, limited natural resources, and unstable markets, which highlights the need for adaptive and intelligent farming systems (Musa & Lim, 2025). Combining advanced tools with local practices offers a sustainable pathway to higher productivity, reduced environmental impact, and stronger resilience for smallholder and Indigenous farmers (Ajayi *et al.*, 2024). A concrete illustration comes from community-based natural resource monitoring, where GIS and remote-sensing data are combined with Indigenous land-management knowledge to track environmental change and support legal recognition of customary land claims demonstrating how advanced tools and Indigenous knowledge can be combined successfully rather than treated as competing inputs (Danielsen *et al.*, 2022; Ferreira & Delgado-Serrano, 2024). Recent studies highlight precision farming, climate adaptation measures, and value-added systems as important innovations that, when paired with Indigenous knowledge and digital tools, can build a more sustainable and equitable future for food production (Aroba & Rudolph, 2024).

Technology can contribute significantly to ecosystem-based agriculture and biodiversity protection in Indigenous territories when it is developed and applied in ways that are community-led, respectful of cultural values, and free from extractive or imposed approaches (Akamani, 2021). Integrating tools such as GIS, remote sensing, biodiversity monitoring, and seed tracking into Indigenous farming has strengthened traditional knowledge, improved agroecological resilience, and supported the long-term sustainability of agricultural landscapes (Haworth *et al.*, 2018). For this reason, to ensure that these innovations contribute to both ecological health and the preservation of Indigenous cultural systems, they must be designed and implemented within ethical, collaborative frameworks that priorities Indigenous leadership at every stage.

Protecting biodiversity and sustaining healthy ecosystems form the foundation for agricultural resilience. However, with climate change intensifying, these ecological priorities need to be paired with adaptive strategies that directly address climate-related risks. For Indigenous and smallholder farmers, whose livelihoods depend heavily on local environmental stability, this means adopting technologies and practices that safeguard both ecosystem integrity and crop productivity. The following section explores how climate resilience technologies,

when combined with local knowledge and guided by community leadership, can help food systems adapt to the impacts of climate change.

Climate resilience technologies

Climate resilience in agriculture has shifted from being an optional consideration to becoming a strategic necessity, particularly for smallholder and Indigenous farmers who face the most severe impacts of climate change. Persistent droughts, changing rainfall patterns, and more frequent extreme weather events threaten not only crop yields but also food security and rural livelihoods. In this context, climate resilience technologies that are accessible, affordable, and culturally compatible provide vital opportunities for adaptation.

a) Drought-resistant crops, water harvesting systems, and micro-irrigation

Adopting drought-resistant crop varieties helps stabilize yields under water stress and conserve local genetic diversity (Raihan, 2024). Micro-irrigation methods, such as drip and sprinkler systems, improve water use efficiency, particularly when combined with traditional calendars and rainwater harvesting (Rajesh *et al.*, 2025). Water harvesting systems, which include rooftop collection, farm ponds, and bunding, are based on Indigenous knowledge and help secure supplies while reducing erosion. When integrated with bioengineered structures such as check dams and vegetative buffers, these approaches strengthen resilience in areas with unpredictable rainfall (Meena *et al.*, 2023). A comparative overview of five key climate resilience technologies is presented in Table 3, outlining their cost, impact, and scalability in Indigenous and smallholder contexts to guide the selection of suitable interventions.

Table 3. Comparative summary of climate resilience technologies in smallholder and indigenous farming contexts

Technology	Cost level	Impact on resilience	Scalability (in indigenous/smallholder systems)	Key notes
Drought-resistant crops	Low–Moderate	High: Improved yield stability under water stress	High: Seed sharing networks and local seed banks enable adoption	Must align with local crop preferences and cultural suitability
Micro-irrigation (drip/sprinkler)	Moderate	High: Efficient water use and improved soil moisture	Moderate: Requires technical support and upfront investment	Best suited when integrated with traditional calendars and practices
Water harvesting systems	Low–Moderate	High: Increases water availability and reduces erosion	High: Can be built with local materials and community labor	Often based on traditional water knowledge and well accepted
Early Warning Systems (EWS)	Moderate	High: Enables proactive climate response	Moderate: Dependent on connectivity and localization	Co-design with local language and formats critical for usability
Bioengineered structures (e.g., check dams)	Moderate–High	Moderate–High: Controls runoff, improves recharge	Moderate: Needs planning and land access agreements	Can complement existing land management practices if community-driven

Sources: Meena *et al.* (2023); Njagi (2018); Raihan (2024); Bhagat *et al.* (2024); Rajesh (2025).

b) Early warning systems (EWS) for weather extremes

EWS combines forecasts, satellite imagery, and mobile alerts to help farmers adjust practices and reduce risks. In Kenya, blending Indigenous weather forecasting with digital platforms increased accuracy and trust (Njagi, 2018). However, barriers such as language differences, poor connectivity, and limited digital literacy reduce

effectiveness. Co-designing systems with local communities, for example through participatory monitoring and familiar channels such as radio programs, makes them more inclusive and actionable (Bhagat *et al.*, 2024).

Post-harvest and value-addition technologies

Building resilience requires going beyond the production stage. Post-harvest losses undermine adaptation gains, while value-added systems increase income and preserve traditional foods that are central to cultural identity. Solar drying technologies, when adapted to local needs, provide a hygienic, low-cost, and energy-efficient method of preserving agricultural products. Unlike traditional open-air drying, which is prone to contamination, spoilage, and uneven quality, solar dryers allow for more controlled conditions that improve food safety, retain nutritional value, and reduce post-harvest losses. These systems are particularly well suited to Indigenous and smallholder contexts because they can be constructed using locally available materials, require minimal external energy inputs, and can be managed collectively at the community level.

Market-oriented strategies such as Indigenous branding, Geographic Indicators (GIs), and ethical labelling not only strengthen cultural identity but also create niche market opportunities that reward biodiversity-friendly practices (Oberoi & Dinesh, 2019). These approaches give farmers greater visibility in competitive markets by differentiating products through cultural narratives and environmental stewardship. E-commerce platforms further expand this potential by enabling direct connections between producers and consumers, bypassing intermediaries and allowing farmers to retain a larger share of profits while highlighting the cultural and ecological value of their products. Evidence from Nigeria demonstrates that integrating digital platforms into value-added supply chains reduced post-harvest losses and significantly increased household incomes over two years (Alawode, 2023).

However, sustaining these benefits depends on supportive infrastructure, digital literacy, access to mobile payment systems, and locally adapted logistics to ensure that Indigenous producers can fully participate while maintaining control over their food systems (Sanusi *et al.*, 2025). Figure 3 presents the post-harvest and value-addition process for Indigenous and smallholder farming systems, from the moment of harvest through preservation, processing, branding, and eventual market access.

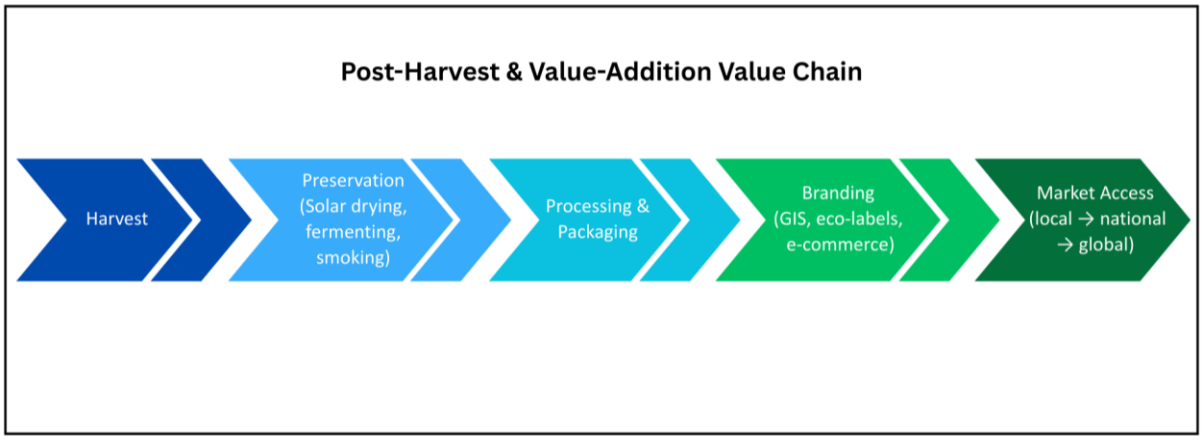


Figure 3. Post-harvest and value-addition value chain for Indigenous and smallholder agricultural products.

Climate resilience technologies, which include crop improvements, water management innovations, Early Warning Systems, and post-harvest value-addition, provide scalable and culturally relevant pathways to strengthen food security and rural livelihoods. Their effectiveness is not limited to technical efficiency but also lies in the way they integrate Indigenous knowledge, traditional practices, and community leadership to ensure long-term sustainability. These approaches help safeguard yields, protect ecosystems, and preserve cultural identity, while also empowering local communities and reducing vulnerability to climate shocks. When adopted through participatory and ethical frameworks, they contribute to economic empowerment, intergenerational knowledge transfer, and stronger social cohesion. As a result, climate resilience technologies move beyond risk mitigation to drive transformative change by aligning global innovations with local realities, supporting sustainable food systems and advancing a more equitable and resilient future for Indigenous and smallholder farmers.

TRADITION MEETS TECHNOLOGICAL ADVANCEMENTS

Agricultural transformation in Malaysia increasingly depends on finding a balance between traditional practices and modern technology. Traditional farming systems embody cultural knowledge, ecological stewardship, and local adaptation, yet they often face economic pressures from rising costs, climate variability, and market competition. Conversely, technological approaches such as precision agriculture promise higher efficiency and profitability but must be adapted to the realities of smallholder and Indigenous communities if they are to be effective. Initiatives led by MARDI demonstrate how low-cost precision tools—such as variable-rate seeding, canopy-based fertilizer application, and GIS mapping—can be introduced through service-provider models, ensuring affordability while raising yields and farm incomes (Rahim *et al.*, 2021).

At the same time, studies in Batang Lupar highlight the enduring role of traditional rice varieties, which provide social and cultural value alongside local food security, even when commercial breeds dominate in terms of yield and profitability. Taken together, these experiences show that the future of agriculture lies not in choosing between tradition or technology, but in integrating them to create production systems that are economically viable, socially relevant, and environmentally sustainable. Few cases presented the importance of linking economic outcomes with cultural realities, ensuring that agricultural innovation supports not only productivity and income growth but also the preservation of local traditions and knowledge.

Case 1: Implementing precision agriculture technology (FELCRA Seberang Perak)

Agriculture in Malaysia is increasingly shaped by challenges arising from climate variability, fluctuating input costs, and the demand for sustainable intensification. Within this context, precision agriculture has emerged as a viable pathway to enhance productivity and resource efficiency. However, affordability and accessibility remain significant hurdles for smallholders and Indigenous farmers. Malaysia's experience through the Malaysian Agricultural Research and Development Institute (MARDI) demonstrates how low-cost precision agriculture systems can be developed and deployed at scale, even in resource-constrained environments. A flagship example is the initiative at FELCRA Seberang Perak, where a comprehensive precision farming package was introduced, integrating Variable Rate Technology (VRT) with Green Area Index (GAI) modeling to optimize rice cultivation.

The package emphasized the use of digital mapping, UAV imagery, and geospatial modeling to refine both seeding and fertilizer application, thereby increasing input efficiency and yield outcomes (Ghazali *et al.*, 2020; Rahim *et al.*, 2021). Importantly, the system was designed to function effectively under Malaysia's large, flat paddy landscapes while ensuring precise application of inputs. The technological approach comprised three major elements:

- *VRT for Seeding based on Land-Levelling*: Field variability was mapped using GNSS-integrated digital elevation models. This enabled seed rate adjustment, reducing density in low-lying areas prone to waterlogging, thereby improving germination and plant uniformity.
- *GAI-Based Fertilizer Application*: UAV and satellite imagery were processed to calculate canopy health via GAI values. These values guided zone-specific nitrogen application, enhancing nutrient efficiency and reducing environmental risks.
- *Integrated GIS Mapping and Field Prescription*: Treatment maps were incorporated into GNSS-equipped machinery, enabling precision-driven input application by farmers or contractors.

A crucial design feature is that the model does not require individual farmers to own high-cost digital tools. Instead, it operates through service-based delivery, where cooperatives or contractors deploy precision equipment across multiple farms. This arrangement significantly reduces costs for smallholders and enhances collective efficiency.

a) Economic impact and monetary benefit

The economic outcomes of the FELCRA initiative demonstrate the tangible value of precision agriculture. A comparative assessment of three treatments—traditional semi-mechanized practices, VRT-seeding alone, and full precision treatment (VRT + GAI)—revealed consistent financial superiority for precision approaches. Gross income per hectare increased from MYR 5,040 (conventional) to MYR 5,676 (full precision). Net income per hectare improved even more substantially, from MYR 2,332.22 (conventional) to MYR 3,352.69 (full precision), representing a 44% increase in profitability.

Table 4. Comparative economic performance of conventional, VRT-seeding, and full precision agriculture treatments in the FELCRA Seberang Perak paddy system.

Indicator/Season	Practice			
	Package 1+2	Package 1	Package 2	Conventional
Area (ha)	1	1	1	1
Net yield (MT/ha)	4.73	4.42	4.53	4.20
Deduction (%)*	25%	25%	25%	25%
Gross income (MYR/ha)[a]	5676	5304	5436	5040
Production cost (MYR/ha)[b]	2,323.31	2,258.03	2,252.34	2,707.78
Net income (MYR/ha)	3,352.69	3,045.97	3,183.66	2,332.22
Benefit cost ratio (BCR)	2.44	2.35	2.41	1.86

Note: Package 1=Levelling & Seeding (VRT), Package 2=Fertilizer application (VRT). Calculation of the viability of rice production with precision agricultural technology refers to the average value for both seasons of 2–2018 and 1–2019 *Quality control/grading process which amount deducted will not include in the payment to the farmers.
Source: Data adopted from Rahim *et al.* (2021).

These results underscore that low-cost precision farming is not only technically feasible but also financially advantageous. By embedding these tools into shared-service models, the initiative enables smallholders to capture higher returns while minimizing input dependency. Importantly, these monetary benefits are achieved without compromising ecological integrity; rather, they align with sustainability objectives by reducing nitrogen runoff and maintaining balanced soil health. For smallholder and indigenous farmers constrained by budgets, this combination of higher income, improved efficiency, and environmental co-benefits represents a compelling transformation pathway, contingent upon the availability of enabling institutions and support systems.

b) Scalability and relevance for indigenous contexts

Although initially deployed in large-scale FELCRA estates, the system offers clear opportunities for smallholder and Indigenous adaptation. More than 80% of Malaysian farmers already rely on service providers for input application and harvesting, offering a strong institutional foundation for expanding VRT and GAI services through cooperative models, extension networks, and subsidized contractors. MARDI's leadership in this initiative highlights the critical role of public research institutions in ensuring that innovation translates into accessibility. By incorporating precision tools into extension strategies and simplifying training materials, MARDI lowered barriers to adoption and enhanced farmer confidence. The GAI-based method, in particular, is promising for indigenous contexts because it mirrors traditional knowledge systems of observing crop vitality, thus creating intuitive alignment between modern digital metrics and long-standing agronomic practices.

This alignment is proposed here as a plausible mechanism for adoption rather than an established finding: to date, no adoption-rate data directly compare GAI-based tools against other precision-agriculture methods on this basis, and testing this hypothesis is identified as a priority for future research. Nonetheless, challenges remain upfront investment costs, weak rural infrastructure, and low levels of digital literacy continue to constrain uptake. Furthermore, cultural compatibility is essential. Tools must be localized in terms of language, spatial frameworks, and decision-making practices to ensure they complement rather than displace traditional stewardship systems. For indigenous and smallholder contexts, precision agriculture can be most effective when embedded within participatory approaches, ecosystem-based management, climate resilience strategies, post-harvest value addition, and low-cost delivery models.

These focus areas illustrate that technology adoption is maximized when it is deeply rooted in community realities. By integrating modern precision methods with traditional ecological knowledge, smallholders can enhance productivity while safeguarding cultural heritage and ecological sustainability. Malaysia's experience at FELCRA Seberang Perak provides a robust case for how inclusive design, rural infrastructure investment, and continuous capacity-building can jointly foster resilient, equitable, and sustainable agricultural systems.

Case 2: Traditional varieties versus commercial rice breed (IADA Batang Lupar)

The Integrated Agricultural Development Authority (IADA) Batang Lupar in Sarawak provides an insightful case of the intersection between indigenous agricultural traditions and the modernization agenda. The region's Iban farmers have cultivated diverse traditional rice varieties for centuries, embedding them within ritual practices, kinship networks, and ecological adaptation (Wahab, Rahim, Syahrin, & Engku Elini, 2025). However, government policy in Malaysia has progressively emphasized self-sufficiency through the adoption of high-yielding commercial breeds, supported by input subsidies and guaranteed markets (Rahim, Engku Elini, Sunian, Nuruddin, & Mohd Amirul, 2022). This dynamic reveals the competing pressures of cultural continuity and economic rationalization.

a) Economic impact and monetary benefit

Rice cultivation in Batang Lupar reflects a trade-off between yield productivity and market value. Traditional varieties yield approximately 1.47 mt/ha, compared to nearly 2.9 mt/ha for commercial varieties observed in comparable schemes such as IADA Kota Belud (Rahim *et al.*, 2022). On the surface, this suggests a clear advantage for modern high-yielding varieties.

Yet, profitability analysis reveals a more complex picture. Traditional rice commands a niche market price of RM4.20/kg, compared to the lower bulk paddy price of commercial strains (Rahim *et al.*, 2022). Assuming complete marketability, traditional rice can generate RM6,174/ha, a figure competitive with subsidized commercial production.

A robust comparison should express profitability on a net-profit-per-kg basis (revenue per kg minus production cost per kg) for both varieties, rather than comparing price and cost side by side as above. (Table 5). The premium price traditional rice commands (RM4.20/kg, against subsistence-scale, thinly traded production) plausibly reflects strong niche and heritage demand, limited supply relative to commercial paddy, and direct sales through local or ritual markets rather than bulk grading channels. The demand mechanism behind each price is explained after Table 5.

Table 5. Net profitability per kilogram of paddy: IADA Kota Belud (commercial benchmark) versus IADA Batang Lupar (traditional), by subsidy scenario

Item	Commercial (Kota Belud)	Traditional — fully marketed (Batang Lupar[a])	Traditional — partly marketed (Batang Lupar[b])
Average yield (mt/ha)	2.97	1.47	1.47 (0.735 marketed)
Average price (RM/kg)	1.14	4.20	4.20
Gross income (RM/ha)	2,911.79	6,174.00	3,087.00
Production cost (RM/ha) — with subsidy	1,665.31	1,163.59	1,163.59
Production cost (RM/ha) — without subsidy	2,846.91	2,345.19	2,345.19
Net income (RM/ha) — with subsidy	1,246.48	5,010.41	1,923.41
Net income (RM/ha) — without subsidy	64.88	3,828.81	741.81
Net profit per kg (RM/kg) — with subsidy	0.42	3.41	2.62
Net profit per kg (RM/kg) — without subsidy	0.02	2.60	1.01

Benefit-cost ratio (BCR) — with subsidy	1.75	5.31	2.65
Benefit-cost ratio (BCR) — without subsidy	1.02	2.63	1.32

Note: a = entire harvest sold; b = 50% of harvest sold, 50% retained for household consumption (net profit per kg for scenario b is calculated on the marketed portion only, 0.735 mt/ha). Net profit per kg = net income per hectare ÷ marketed yield per hectare. Source: Farm-household survey underlying Rahim *et al.* (2022).

Table 5 completes this comparison on a net-profit-per-kg basis, using the underlying farm-household survey data behind Rahim *et al.* (2022) and Mohd Amirul *et al.* (2025). Commercial rice at the IADA Kota Belud benchmark (2.97 mt/ha, RM1.14/kg bulk paddy price) returns a net profit of only RM0.42/kg with subsidy, falling to RM0.02/kg without subsidy once the ~14% grading deduction and input costs are accounted for. Traditional rice in Batang Lupar (1.47 mt/ha, RM4.20/kg niche price) returns RM3.41/kg with subsidy and RM2.60/kg even without subsidy when the full harvest is marketed, and still RM2.62/kg (with subsidy) or RM1.01/kg (without subsidy) under the more realistic scenario in which half the harvest is retained for household consumption. On a net-profit-per-kg basis, traditional rice is therefore markedly more profitable than commercial rice at both farm gates despite its much lower yield per hectare — the opposite conclusion from a yield-only or gross-price comparison, and the central reason the net-profit-per-kg framing matters.

The two prices reflect different demand mechanisms. Commercial paddy is absorbed through a bulk, subsidy-supported channel: millers and granary buyers purchase at a standardised price subject to quality grading (averaging a 14% deduction), with government paddy-input subsidies (about RM1,446/ha nationally) offsetting what would otherwise be a very thin margin. Traditional rice is not sold into this bulk channel at all: survey data indicate that much of the Batang Lupar harvest is either consumed at home or sold in small volumes directly within the local community, at a price that reflects heritage and ceremonial value — including use in semangat padi rice-spirit rituals — as much as caloric supply. The limited, geographically confined production of Sarawak's traditional varieties further constrains supply relative to commercial paddy, which keeps this niche price stable rather than exposing it to bulk-market competition.

Moreover, production costs for traditional varieties remain lower, as they rely on household labor and minimal purchased inputs, such as fertilizer or mechanization (Mohd Amirul *et al.*, 2025). By contrast, commercial rice production in Batang Lupar is heavily reliant on subsidies. With support, production costs average RM1,163.59/ha, but would nearly double without government assistance (Rahim *et al.*, 2022). This dependency underscores the fragility of commercial rice economics in non-granary areas, where natural conditions are less suited for high-input systems.

The resilience argument for traditional rice is strengthened below with household-level evidence from the same underlying farm survey (Table 6).

Table 6. Socio-demographic and livelihood profile of rice farming households, IADA Batang Lupar (n=62)

Characteristic	**Category**	**% of respondents**
Age	51 years and above	62.7
Gender	Female	30.2
Ethnicity	Bumiputera Sabah & Sarawak	82.3
Education	Primary school only	41.9
Household size	4–6 members	58.1
Dependents	3 or fewer	69.4
Primary occupation	Full-time rice farming	95.2
Secondary occupation	Other crop farming	43.5

	Non-farm (trade, government/private sector, other)	43.5
	Rice farming	12.9
Farming experience	21–30 years	32.2
	More than 40 years	8.5
Family labor used in rice cultivation	3 or fewer family members	93.5

Source: farm-household survey underlying Rahim *et al.* (2022) and Mohd Amirul *et al.* (2025), n=62 Batang Lupar respondents (2020 survey round). Secondary-occupation categories sum to approximately 100%, indicating that almost every surveyed household reports some income activity beyond rice farming itself.

Table 6 summarizes the socio-demographic and livelihood profile of the surveyed Batang Lupar households. The clearest resilience-relevant finding is income diversification: only 12.9% of respondents' secondary occupation is rice farming itself, while 43.5% farm other crops and a further 43.5% work in trade, government or private-sector employment, or other non-farm activity, indicating that household livelihoods in Batang Lupar are not dependent on rice income alone. Farming tenure is also long (32.2% report 21–30 years of experience and a further 8.5% report more than 40 years), and production relies overwhelmingly on family rather than hired labour (93.5% of households use three or fewer family members), consistent with rice cultivation being embedded in intergenerational household structures rather than run as a purely commercial enterprise. At the same time, the survey instrument did not collect direct measures of expenditure smoothing or shock vulnerability (for example, savings, debt, or consumption data across lean seasons), so this remains an explicit gap: the income-diversification evidence above strengthens the resilience argument, but dedicated household livelihood indicators are identified as a priority for future data collection (see Concluding Remarks).

Table 7. Traditional versus commercial rice varieties in IADA Batang Lupar, Sarawak

Dimension	**Traditional Varieties (Local/Iban Rice)**	**Commercial Varieties (High-Yielding/Modern)**
Yield (mt/ha)	Lower (~1.47 mt/ha)	Higher (~2.9 mt/ha, Kota Belud benchmark)
Market Value	High niche value (~RM4.20/kg)	Lower bulk price (standard paddy)
Input Needs	Low inputs, manual tools (ketap)	High fertilizer, pesticide, mechanization
Cultural Role	Sacred (semangat padi), identity rituals	Modernization, tied to subsidies
Resilience	Adapted to tidal flooding, ecologically diverse	Vulnerable to pests and monocropping risks

Source: Mohd Amirul *et al.*, 2022; Rahim *et al.*, 2022

This comparison demonstrates that economic profitability cannot be evaluated on yield alone. Traditional varieties sustain livelihoods through reduced dependence on external inputs and resilience in local markets, while commercial varieties remain viable primarily within subsidy-supported frameworks.

b) Scalability and relevance for indigenous contexts

The scalability of commercial rice in Batang Lupar is tied closely to state intervention. Mechanization services, fertilizer subsidies, and extension programs have facilitated adoption among larger landholders, but smaller households face constraints of credit and risk-bearing capacity (Rahim & Sabri, 2025). The dependency on external inputs also raises concerns about long-term sustainability, particularly as climate change increases vulnerability in tidal floodplains. By contrast, traditional rice varieties are scaled differently. Their continuity depends on community seed exchange, ritualized planting cycles, and knowledge transmission across generations (Ranteallo *et al.*, 2020).

While not designed for mass commercialization, they ensure food sovereignty and cultural resilience, particularly among poorer households that cannot afford input-intensive farming (Mohd Amirul *et al.*, 2025). From an indigenous perspective, the persistence of traditional rice cultivation is not merely about economics, but about maintaining identity and ecological stability. Farmers often adopt dual strategies, cultivating commercial rice for the market while reserving traditional varieties for domestic use and rituals. Such pluralistic systems strengthen adaptive capacity and highlight the need for policies that support but not replace indigenous practices (De Falcis *et al*., 2025).

The Batang Lupar case illustrates that agricultural modernization is not a binary choice between tradition and innovation. Traditional rice remains indispensable for household security, cultural identity, and ecological resilience, while commercial rice aligns with national food security policies and short-term income generation. The challenge for policymakers lies in supporting coexistence strategies: conserving traditional varieties through seed banks and cultural recognition, while ensuring commercial systems are inclusive and resilient. This balanced approach affirms that innovation and tradition can function not as rivals, but as complementary pathways toward Malaysia's food security goals.

CONCLUSION

This paper makes a simple claim with large consequences: agricultural innovation endures only when it is context-sensitive—anchored in cultural relevance and ecological sensitivity. These are not parallel concerns; they are interdependent. Culture shapes how technologies are understood, trusted, and used. Ecology sets the thresholds within which agriculture can thrive without eroding its own foundations. When both are respected, productivity gains are more than temporary—they become durable. The cases discussed show why. Where ecological functions are treated as expendable, or where local knowledge is reduced to ritual without authority, interventions falter despite technical promise. Where traditions are recognized as living knowledge systems and ecological limits are designed into decisions, the same interventions gain legitimacy, travel further, and last longer. The lesson is not "choose tradition over technology," but "design technology that learns from tradition and stays inside ecological boundaries."

The paper's specific contribution is the cultural-relevance/ecological-sensitivity framework developed in the Approach section above and applied across the FELCRA and Batang Lupar cases: rather than treating "context-sensitivity" as a single attribute, as much of the existing enabling-factors/barriers literature does (Rurii & Muasya Nzengya, 2026), this paper treats it as the joint product of two distinct and independently necessary conditions, and shows through contrasting technology-anchored and tradition-anchored cases how the same framework applies at both ends of that continuum. This differs from prior single-case studies of either precision agriculture or traditional rice systems in Malaysia by making the comparison, and the underlying framework, explicit.

The policy implication is clear: move from citing traditional knowledge to operationalizing it. This means giving communities a seat and a say in how solutions are shaped; aligning incentives to outcomes that matter (soil health, water balance, agro-biodiversity, livelihood stability); and setting safeguards so financial tools—subsidies, insurance, market access—do not unintentionally reward ecological overshoot or cultural displacement. Standards, metrics, and monitoring must be recalibrated to capture social-ecological performance, not yield alone. For research, the priority is trans-disciplinary work that is place-based and longitudinal. Field labs and living landscapes should test how design choices travel across seasons and shocks, not just trial plots. Data systems must be ethical and reciprocal—co-owned with farming communities, governed by clear benefit-sharing, and used to answer locally meaningful questions. Evaluation should report on resilience, equity, and ecosystem function alongside efficiency.

Future work should test whether this framework travels beyond rice: priority directions include applying it to other Malaysian commodity crops (e.g., oil palm smallholdings, upland vegetable systems), validating the GAI–traditional-observation adoption hypothesis raised in the FELCRA case with field adoption data, and extending the household-level resilience evidence flagged in the Batang Lupar case through dedicated livelihood surveys. In particular, the potential alignment between GAI-based agricultural tools and traditional observation systems should be treated as a research hypothesis rather than an established adoption mechanism. Future studies should generate comparative field evidence, including adoption-rate data and user acceptance assessments, to determine whether such culturally aligned digital approaches provide measurable advantages over conventional precision-agriculture methods.

For practice and markets, the work is to make adoption feasible. Service models that lower upfront costs, capacity building that grows local expertise, and value chains that pay for quality, origin, and stewardship can convert good ideas into lived improvements. Post-harvest systems, circular use of resources, and careful use of digital tools can reduce loss and pressure on ecosystems—provided they remain accountable to place and people. Equity is the through-line. Smallholders and indigenous communities carry disproportionate climate and market risk while holding knowledge essential to sustainable futures. Innovation that does not improve their security, voice, and returns is incomplete by design. Strengthening rights to land and water, building fair finance, and institutionalizing co-creation are not add-ons; they are preconditions for success.

In short, the path forward is not a contest between tradition and technology but a choreography between them. If we commit to designing with culture and within ecology, Malaysia can shape an agricultural future that is productive without being extractive, modern without being forgetful, and resilient without leaving anyone behind.

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