A Holistic Framework for Agricultural Transformation: Validating the Framework for Agricultural Revolution and Management (FARM) Model for Sustainable Innovation

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ABSTRACT

The agricultural sector in Penang, is undergoing transformative shifts driven by the need for sustainable innovation and increased productivity. This study introduces and validates the Framework for Agricultural Revolution and Management (FARM) Model which outlines six key pillars essential for agricultural advancement: Workforce & Skills Dynamic, Technological Integration, Operational Efficiency & Productivity, Economic Sustainability, Policies & Regulatory Support and Environmental & Infrastructure Readiness. Adopting a holistic research approach, the study integrates qualitative interviews with farm operators, stakeholder engagement, seminar-based dialogue, member checking and peer review to ensure the credibility and relevance of findings. A stakeholder seminar titled Enhancing Farm Operations: Overcoming Barriers to Agricultural Innovations was held with representatives from government agencies, financial institutions, industry experts, and farmers. The insights gathered reinforced the six pillars of the FARM model, confirming that knowledge gaps, limited financing, policy misalignment, infrastructure shortfalls, and complex technologies remain significant barriers. Stakeholders emphasized the need for user-friendly tools, specific policies, cooperative structures, and stronger advisory support. The study's findings are further strengthened by active collaboration with the Department of Agriculture Penang, which supported the recommendations and agreed to future partnership efforts. The triangulated validation process confirms that the FARM model accurately captures the multifaceted challenges and solutions in agricultural innovation. This research contributes a practical and theoretical implication that can guide policymakers, practitioners, and researchers in shaping future agricultural strategies in Penang and beyond, rooted in local context and inclusive stakeholder engagement.

Keywords: Agricultural Innovation, Farmer Empowerment, Policy Support, Smart Farming, Technology Adoption

INTRODUCTION

Agriculture is a fundamental sector that sustains food security, supports rural livelihoods, and contributes to national economies. However, the industry faces mounting challenges such as climate change, labor shortages, land degradation, and rising production costs. These issues have pushed global and local stakeholders to explore innovative and sustainable farming solutions (FAO, 2023). In Penang, the agricultural landscape is shaped by small and medium-sized farm operators who face specific constraints in adopting modern practices. These include limited access to information, weak digital infrastructure, high cost of technologies, and rigid policy structures (Ministry of Agriculture and Food Security, 2024). Addressing these barriers requires a comprehensive and context-sensitive approach that goes beyond isolated interventions.

This study introduces the Framework for Agricultural Revolution and Management (FARM) Model, which is developed to capture the core pillars influencing the transformation of farm operations. The six key components Workforce & Skills Dynamic, Technological Integration, Operational Efficiency & Productivity, Economic

Sustainability, Policies & Regulatory Support and Environmental & Infrastructure Readiness form an interconnected system that defines innovation readiness in agriculture. To ensure the relevance and accuracy of the model, this research employed a holistic methodology involving stakeholder interviews, seminar engagement, member checking, peer review, and validation surveys. The seminar held in Penang served as a live platform to verify findings and gather input from various actors, including government agencies, researchers, financial bodies, and farmers themselves.

The findings emphasize the urgent need for coordinated efforts to modernize agricultural practices in a way that reflects local realities. Through the FARM Model, this paper offers a strategic framework that not only addresses existing barriers but also lays the groundwork for a more inclusive, resilient, and technology-driven agricultural future (Ismail, R., Ahmad, N., & Lim, K. H. (2024); World Bank, (2023).

Background of the Study

The global agriculture sector is facing numerous issues due to external and internal impacts, such as food crises, climate change, geopolitical factors, ever-changing customer demands, changes in company directions, increased regulatory pressures by the governance body, and many others, which have resulted in several catalysts for change. Climate change results in decreased agricultural output and changing food sources, raising food insecurity and health concerns (Zhu, Burney, Chang, Jin, Mueller, Xin, Xu, Yu, Makowski, & Ciais, 2022).

In recent years, agricultural research and development have become critical issues, particularly in response to expanding global market demands and the broader need for innovation (Passarelli, Bongiorno, Cucino & Cariola, 2023). Numerous scholars have examined the adoption of emerging technologies in agriculture (Calisti et al., 2020; Wang & Fan, 2021; Hackfort, 2021; Tenakwah et al., 2022). This is a complex issue influence by a wide range of factors that can affect whether a given technology is accepted or rejected.

Existing farming systems are increasingly recognized as incapable of addressing the concerns of food sustainability and security. The farming system might be severe and broad, but the goal remains the same: to raise enough food to maintain the rising population all year (MacDonald, 2023). It is a well-known fact that farm operators' attitudes toward technology impact their decisions whether to accept or reject innovations. Meanwhile, modern farm operators face numerous challenges, such as obtaining a remunerative price for their produce, the effects of climate change, competition with large farm players, and increased pest and disease resistance (Karthikeyan, 2023).

Therefore, one of the important criteria in this context is the need for enhanced innovations, or specifically, smart agriculture, which is frequently given by the placement of innovations or the use of the Internet of Things (IoT) in the agricultural sector. In agricultural applications, the integration of AI and IoT is largely concerned with regulating harvests, greenhouse parameters, and smart fertigation systems to stimulate reactions to any changes in external circumstances. For example, convolutional neural networks are to analyze IoT-generated data to forecast and identify potential crop illnesses across various scales of operation (Adli, Remli, Wan Salihin, Wong, Ismail, González-Briones, Corchado & Mohamad, 2023).

METHODS

The primary data gathering method employed in this study was semi-structured, in-depth interviews. These interviews were carried out with agricultural companies/farm operators engaged in crop activities across Penang. A preliminary list of twenty-five (25) crop-focused agricultural companies were obtained. As noted by Dursun (2023), interviews are a commonly preferred method for data collection in qualitative studies due to their depth and flexibility. The interviews took place both on-site at the participants' farms and virtually via Google Meet. Each session lasted approximately forty-five (45) to sixty (60) minutes. According to Gray, Wong-Wylie, Rempel, and Cook, 2020, online video conferencing provides ease, enhanced accessibility, improved personal interaction, and time efficiency, making it a cost-effective and practical alternative to in-person interviews in

qualitative research. Follow-up phone calls significantly improve survey completion rates (Neal, Neal, & Piteo, 2020). Interview quotes were recorded exactly as spoken to maintain authenticity. Although software like

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NVIVO and Atlas.ti can assist in qualitative analysis, this study used manual analysis and cross-checking due to the small number of participants.

The interview questions were structured using the funnel model, starting with broad, open-ended questions and gradually narrowing down to more specific questions as the conversation developed. Probing questions were used to elicit deeper insights, often yielding unfiltered responses that provided rich, descriptive data reflecting the participants' emotions.

In parallel with the data collection, the researcher actively engaged with the agricultural conferences, seminars, webinars, and expos. These efforts contributed to building a professional network and gaining contextual understanding within the field. The following Table 1 presents the data on the interviewed participants.

Table 1: Participants' Profile

ID	Gender	Age	Race	Designation	Farming Experience	Farm Size (acres)	No of Workers	Adopt Technology
F1	Male	60	Chinese	CEO/ owner	8 yrs	5.0	13	Yes
F2	Male	46	Chinese	Founder	7 yrs	2.0	3	Yes
F3	Male	33	Chinese	Owner	6 yrs	20.0	20	Yes
F4	Male	31	Malay	Owner	9 yrs	6.4	4	Yes
F5	Male	45	Malay	Owner	1 yr	1.0	2	Yes
F6	Male	24	Chinese	Engineer	1 yr	20.0	25	Yes
F7	Female	54	Malay	Owner	12 yrs	5.0	3	No
F8	Male	68	Chinese	Director	38 yrs	18.0	4	No
F9	Male	47	Malay	Owner	5 yrs	5.0	3	No
F10	Male	51	Chinese	Owner	30 yrs	5.0	3	No
F11	Male	30	Chinese	COO	5 yrs	6.0	11	Yes

The participants' designation, farming experience, and awareness or knowledge of adopting technology were major data points in this study, as they help identify who is responsible for making decisions regarding innovation adoption on each farm. Meanwhile, information on farm size and the number of workers provides insight into the scale of farm and operations.

The researcher started analyzing the data concurrently with ongoing data collection to ensure that data saturation could be reached. After gathering responses from six (6) participants, the researcher began the first step of data analysis, which involved transcribing the data. This process of comparing one transcription to another had been repeated with the remaining participants' inputs until the researcher observed that the inputs from the tenth (10^{th}) participant were becoming similar to the previous ones and no new data were derived.

However, researcher still proceeded with one more participant to confirm that there were no more new data that could be collected and then stopped at Participant Eleven (11). The researcher grouped together all the data, where those with similar dimensions and given preliminary names eventually became categories. The purpose of doing this was to find patterns in the data. In order to construct the patterns and categories, the researcher then used the grounded theory approach, specifically open, axial, and selective coding, which details are further explained in this chapter.

Open Coding

Open coding is the first phase of qualitative data analysis in which the researcher divided the data into several units of meaning. Throughout this procedure, the researcher carefully examined the data, particularly during interviews, and labels relevant concepts, feedback, views, or thoughts with descriptive codes. These codes reflect what is happening in the data and are frequently used as keywords.

The purpose of open coding is to discover patterns, themes, and classifications that arise from the data without making presumptions. This stage prepares the groundwork for further analysis by dividing raw data into

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manageable and useful parts. During this research, the researcher transcribed all the organized codes into an Excel spreadsheet for simple viewing and sorting.

During the open coding stage, frequent sentences were gathered and summarized to form common themes. Answers received from questions based on the number of items cited repeatedly among all participants were grouped according to the research questions for simplicity of further coding in the next stage.

Table 2: Open Coding

RQs	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
RQ1: How does human perceptions, attitudes, and preferences towards AI systems integrates in the agriculture sector to make decisions?	Labour Shortage	Communications	High Cost	Farm Monitoring	Create Awareness	Create Awareness	Reduce Labour Cost	Training	Easy Daily Task	Reduce Costs	Reduce Costs
	Lack of Skills	Understanding	Save Cost	Reduce Workers	Reduce Cost	Demo Set	Shortage of Workers	Young Farmers	Crop Match with Technology	Simple to Use	Reliability
	Increase Revenue	Young Farmers	Save Time	Save Time	Reduce Workers	Understand the System	Lack of Information		High Cost for Technology	Save Time	ROI
	Increase Income	Result	Reduce Workers	Save Cost	Save Time	Rely on AI	Information		Simple System	Improve Yield	High Initial Cost
	Improve Efficiency	Profit	Using Sensor	Ease Tasks	Ease of Monitoring Farm	Improve Productivity	Exposure		Location	Experience	Increase Produce
	Risk Mitigation	Boost Production	Save Fertilizers Use	Based on Experience	Easy to Handle	Easy Start for Beginners	Demo Set		Simple Technology	Weather Report	Traditional Knowledge
	Optimize Operations	Improve Quality	Increase Produce	Less Use of Fertilizers	Rely on AI		Reduce Cost		Simple Tasks	Conversations	Hands-on
	Track Record of Yield	Provide Solutions	Reduce Import	Reduce Operation Cost			High Set-up Capital		Increase Productivity		
	Sceptical Initially	Don't Rely on AI	Monitor Price				Easy Daily Tasks		Healthy Produce		
	Accepting Gradually	Weather Conditions					No Skilled Workers		Quality Produce		
		Climate Issues					Hands-on Experience				
		Data to Make Decision									
		Drone									
		Robots									
RQ2: What are the factors that influences the adoption of AI innovation in the	Profit	Profit Loss	Investment	High Installation Cost	High Initial Cost	Increase Revenue	Save Cost	Drain	High Costs	High Costs	High Initial Investment
	Stable Income	Sustainability	Maintenance Cost	Long ROI	Maintenance Cost	Reduce Cost	Easy Tasks	Fear of Risks	Subsidies	Easy to Use	High Labour Costs
	Stable Output	Consistency	Skilled Workers	System by Government	High Operation Cost	Reduce Workers	Getting Skilled Workers	Lack of Knowledge	Government Programs	Easy to Maintain	Save Water

agriculture sector?	Increase Productivity	Quality	Greenhouse System	Training	Advisory Support	Increase Demand	Government Involvement	Foreign Workers	Incorrect Subsidy	Good ROI	Save Fertilizers
	Literacy Level Increase	Policies Control	Government No Roles	Good Infrastructure	Discipline	Government Involvement	Roads	Pests Issues	No Expertise	Reduce Labour	Subsidies
	High Skilled Jobs Creation	Regulations	Automation	Friends	Location	Interaction with Farmers	Fencing	Workers Quarters	Training	Subsidies	Grants
	Clear Framework of AI Usage	Food Security	Sensor		Connectivity	Funding	Workers Quarters		No Skilled Workers	Trainings	Programs
	Sync Syllabus with IHLs	Education	Training		Water	Internet	Cost Savings			Government Programs	Clear Policies
	Exporting Local Produce	Funding	Source of Information		Electricity	Access Roads	Threats by Insects			Financial Aid	Data Security
	National Food Security Incentives	R&D	Internet Connectivity		Status	Security	Increase Outputs			Internet	Internet
	Connectivity (5G Internet)	Voice of the People	Friends			Road Infrastructure				Traditional Passed on	Power Source
	Young Farmers Experts in Technology	Access Outside Market	News			Social Media Awareness				Family	Affordable IoT
	Traceability,									Perceptions	Traditional Methods
	Food Source									Don't Trust Tech	Hands-on
	Food Safety and Security										
	Healthy Food										
	Organic Food										
RQ3: How does AI integration in agriculture lead to higher productivity and sustainability?	Labour Shortage	None in Malaysia	Systems Outdated	System Accuracy	Connectivity	Maintenance Cost			Fertilizers	Costly	Reliability
	Increase Revenue	Change Mindset	Increase Quality	Reduce Operation Cost	Electricity	Upgrading the System			Yearly Supply	Expensive Equipment	Accuracy
	Increase Income	Increase Revenue	Monitor Plant Health	Increase Produce	AI	Save Cost				Lack of Information	High Initial Set-up
	Improve Efficiency	Increase Production	Require Manpower	AI	Sustainability	Slow ROI				Funding	Learning Curve
	Risk mitigation	AI into Drone		IoT	Spreading Technology	Increase Production				Reduce Use of Pests	Increase Productivity
	Optimize Operations	Measure Nutrients				Farm Managing Apps				Predict Weather	Reduce Plant Diseases

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	Track Record of Yield	Fertigation				Packaging				Cut Down Waste	Sustainability
	Sceptical Initially					Irrigation System				Reduce Water	Drones
	Accepting Gradually									Save money	Robotics Reduce Labour
										Simple System	Reduce Cost
										Affordable	
										Tailored Small Farms	
										Reduce Waste	
										Save Resources	
										Save money	
RQ4: How does the artificial intelligence (AI) tools and applications that currently being used in agricultural practices improving productivity and sustainability	IoT	Not Much in Use	Sensor	Venturi Injector	Smart Tank	Farm Managing Apps	Image of the Farm		Reduce Water Usage	Increase Productivity	Predictive Analytics Tools
	Sensor	Data Collection	Weather Station	Automation	Mist Spray	Increase Produce			Less Use of Fertilizers	Efficient	IoT Sensors
	Faster Decision Making	Data Analyzing	Increase Productivity	Fertigation Accuracy	Increase Produce	Customized Systems			Good Monitoring	Reducing Guesswork	Real Time Monitoring
	Shorten Learning Curve	Minimize Human Errors	Social	Increase Produce	Reduce Workers	Demo Set			Efficiency	Reduce Waste Resources	Streamline Operations
	Automatic Monitoring	At Infancy Stage	Expensive Equipment	Calibrate the System	Save Cost	Hands-on Experience			Predict Weather	Monitor Crop Health	Real Time Data
	Reduce Water Usage (Rain Harvesting)	IoT to Measure Sensor		Exposure	Increase Productivity	High-Cost Equipment			Spotting Pests/ Insects	Predict Potential Problems	Better Decision Making
	Renewable Energy (Solar)			Demo Set					Uncertain Price	Reduce Chemicals	Optimize Resources
	Pesticide free								Price Hike	Save Cost	Control Overuse Chemicals
	Yield								High Demand	Easy to Use	Reduce Water Waste
	Economic									High Yield	Cost
	Investment								Unsuitable Soil for Crops	Reduce Workers	Ease of Use
										Hands-on Training	ROI

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										Market Demand	Reduce Input Costs
										Consumer Preferences	Increase Productivity

Here are the examples of the process of open coding;

Table 3: Process of Open Coding

Person	Conversation	Open Coding
Researcher	*Aaa… what are the primary factors that influencing farm operators' perceptions of AI?*	
Participant 3	*Like I said just now, to* ***save on manpower, cost, time,*** *so, major is that three things because we are running a business, so we are going to save cost and also to ensure that we can generate the high quantity*	Save cost, save time, reduce manpower

The process described here shows that codes are formed directly from the data, rather than what the researcher wants to find. For example, when Participant 3 said, *"to save on manpower, cost, and time"*, the researcher codes exactly "save cost, save time, and reduce manpower" rather than assuming another meaning such as "efficiency" or so on. The researcher's perspective is interpretative yet controlled, with meaning obtained from facts without pressing it. The researcher also labels the topics directly based on what the participants say. The researcher's bias is addressed through reflexivity and openness

Axial Coding

Axial coding is the next stage in qualitative research where researchers refine and organize open codes by identifying relationships between them. It connects categories and subcategories to better understand the central phenomenon. In this study, axial coding helped identify factors influencing innovation adoption among farmers (see Table 4). The process involves constant comparison of data to develop and refine categories, allowing for deeper engagement with the data and revealing complex relationships between themes.

Table 4: Process of Axial Coding

Person	**Conversation**	**Open Coding**	**Axial Coding**
Participant 1	*Trigger them to use AI aahh… many things la, you know, labour shortages for example, they need AI to help them to reduce the labour. And also, shortages in terms of expertise and technical knowledge you need to… and also, they need to use AI to help them to optimize their* ***operation*** *so that you know they can actually push the revenue and also the income*	High operation costs	
Participant 4	*At this point in time, I see that in getting one system for IoT* ***the cost is very high, so, considering installing*** *the IoT and to get the return of the investments will take a long time.*	High installation and set-up/ initial costs	Financial Concern
Participant 6	*Achieving productivity…. challenges, I think the main challenges is the* ***maintenance,*** *yes, because if you say to remain the technology in farm, yes need to remain but then aaa…. we don't know that how long the technology can stay, maybe one to two years, maybe five to ten years, not sure, you have to… aaa… the technology has to upgrade and also updating the AI also aaaa… I think this is one of the challenges. All these involve costs.*	High maintenance costs	

The researcher used axial coding to detect patterns and linkages in the original codes. This phase enabled the connecting of conceptually comparable codes into more abstract and analytically powerful categories. As a consequence, about seventeen (17) separate axial coding emerged, each reflecting a key component of the participants' experiences and perspectives of Human-AI integration in Penang's agriculture industry. An overview of the axial codes and the related subcategories is shown in Table 5 below.

Table 5: Axial Coding

Categories	Sub-Categories
1. Financial Concern	High installation and set-up/ initial costs High operation costs High maintenance costs Cost savings
2. Business Growth	Stable Income Increase revenue Good return on investment (ROI)
3. Financial Support	Funding Grants Subsidies
4. Challenges	Pest issues Outdated systems Unpredictable weather
5. Demand	Increase demand Access to outside market
6. Simplicity	Easy to use Ease to handle Easy to maintain
7. Labour	Reduce workers No skilled workers Labor shortage
8. Productivity	Improve productivity Stable output
9. Quality	Improve quality
10. Technology	Using of technologies (IoT, Drones, Sensors, Weather Stations) Great monitoring systems (farm, plant health, price, etc) System accuracy
11. Efficient	Save time and costs Consistent Optimize operations
12. Sustainability	Save resources (water, fertilizers renewable energy, etc) & reduce waste Food safety and security Climate issues
13. Policies	Clear regulations and policy control Government advisory support Government programs
14. Infrastructure	Good physical infrastructure (access to road, drain, demo set) Good connectivity (internet, water, electricity Security (fencing) Workers quarters
15. Technophobia	Mistrust of technology Fear of taking risks
16. Experience	Hands-on experience Passed down by family/ tradition Influenced by friends, news and social media
17. Exposure	Lack of knowledge Require training and awareness about the technology

Selective Coding

Selective coding is the final stage of qualitative research, where researchers integrate previously identified themes into a core category that captures the central phenomenon. This step aids in forming a theoretical framework and clear narrative grounded in empirical data. (Adams & Thompson, 2022). It simplifies complex

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relationships by focusing on data relevant to the main category, creating a usable model for real-world applications (Patel & Singh, 2021).

Table 6: Selective Coding

Selective Coding	Categories
Economic Sustainability	Financial Concern Financial Support Business Growth Demand
Technological Integration	Technology Ease of Use Exposure Experience Technophobia
Operational Efficiency & Productivity	Efficient Productivity Quality
Environmental & Infrastructure Readiness	Sustainability Infrastructure
Workforce & Skills Dynamics	Labor
Policy & Regulatory Support	Policy Changes

In this study, selective coding was used to identify the key themes. From the seventeen (17) categories developed from axial coding, this study developed six (6) new key themes; economic sustainability, technological integration, operational efficiency and productivity, environmental and infrastructure readiness, workforce and skills dynamics, and policy and regulatory support that influence the adoption of AI-driven solutions in agriculture. These themes clarify the interaction between human factors and AI, offering practical insights for future developments.

Economic Sustainability

The theme of Economic Sustainability explores the key financial considerations and challenges associated with integrating AI into agriculture. While AI technologies offer the potential to boost productivity and operational efficiency, farmers are significantly concerned about the high costs of implementation, including equipment purchases, installation, setup, and long-term maintenance. For example, while AI-based pest control systems promise improved precision, they require substantial financial investment, leading many farmers to hesitate due to uncertainty over whether potential yield gains and cost savings will justify these upfront expenditures. To alleviate these financial barriers, mechanisms such as government grants, subsidies, and low-interest loans are seen as critical. Many farmers actively seek this support to offset initial costs, with targeted subsidies like those for AI-driven irrigation systems potentially encouraging experimentation with innovative methods that would otherwise be deemed too risky.

In addition to financial support, farmers' fundamental motivation plays a dynamic role in AI adoption. Their willingness to implement these technologies is closely tied to their goals of increasing revenue, ensuring consistent income, and achieving a return on investment. If AI tools demonstrate clear improvements in profitability and long-term business viability such as through enhanced crop health monitoring or increased yields, farmers are more likely to adopt them, even if the costs are high. Furthermore, market dynamics significantly influence adoption decisions. When farmers perceive that AI can help them meet rising consumer demands for high-quality or sustainably produced goods, they become more open to investing in such technologies. The expanding market for organic products, in particular, creates opportunities for farmers to use AI for better quality control, enabling them to command higher prices and tap into premium markets.

Technological Integration

The theme of Technological Integration in agriculture encompasses various factors that either support or hinder the adoption of advanced innovations based on their alignment with farmers' needs, resources, and business objectives. Technologies such as IoT sensors, drones, and precision farming tools offer substantial benefits, including increased productivity, better resource use, and improved crop quality. For instance, sensors can provide real-time data on soil moisture and pest presence, while drones help identify diseases early by offering aerial imagery. However, these tools often require significant financial investment, infrastructure, and technical know-how, making them inaccessible to smaller or traditional farms. Cost and complexity, especially regarding operation and maintenance are major restrictions, particularly for technologies like drones. Adoption likelihood increases when technologies are affordable, easy to use, and supported with local-language interfaces. Farmers prefer practical, app-based tools for tasks like crop monitoring or irrigation scheduling, especially when these come with user-friendly dashboards and guided instructions.

Another crucial aspect is farmers' exposure to technology and their past experiences with it. Limited awareness or understanding often leads to mistrust or reluctance, whereas firsthand exposure through demonstration farms or peer-sharing networks can increase confidence and interest. Seeing technology succeed in local contexts, such as drone applications on nearby cash crop farms, reinforces its perceived usefulness. Social media and local networks can also play a role in spreading success stories. Farmers with positive experiences using simpler tools like digital crop monitoring are more likely to try more complex systems such as automated machinery. On the other hand, technophobia driven by fear of failure, cost, or loss of control over traditional practices can significantly hinder adoption. Concerns about malfunction, data misuse, or overreliance on machines, especially in tightly knit farming communities like those in Penang, also contribute to resistance. In such settings, data privacy worries further complicate the willingness to embrace digital agriculture, especially when the benefits are not clearly understood or communicated.

Operational Efficiency and Productivity

The theme of Operational Efficiency and Productivity emphasizes the critical role that technological innovation plays in enhancing agricultural performance, profitability, and sustainability. Farmers are motivated to adopt new technologies because of their direct impact on production and cost management. Innovations such as GPS-guided tractors and drones that target specific areas for fertilization improve resource utilization, minimize waste, and enhance crop health. These tools help farmers reduce input costs while maintaining or increasing yields, thus operating more efficiently with less labor and at lower expenses. This efficiency is particularly important in the context of rising labor and input costs, making modern farming methods essential for long-term resilience and sustainability.

Increased productivity through innovation allows farmers to optimize outputs per unit of land, labor, or resource, leading to greater yields and higher sales. For example, yield monitors on chili farms help identify areas of varying productivity, enabling better input allocation and improved overall output. Enhanced productivity not only supports higher revenue and profitability but also opens opportunities for market expansion and scaling up operations, especially in competitive, high-demand sectors like cash crops. Furthermore, improved crop quality driven by technologies like biological pest control contributes to better post-harvest durability, healthier produce, and higher market value. Quality crops can access premium or export markets and meet growing consumer

expectations, while also promoting soil health and environmental sustainability. Thus, innovation boosts both immediate economic gains and the long-term viability of farming practices.

Environmental and Infrastructure Readiness

The ability to sustain farming practices through targeted physical and technological support directly underpins long-term productivity, environmental stewardship, and the overall viability of agricultural operations. Farmers committed to sustainability increasingly adopt technologies such as solar panels for powering irrigation systems that reduce reliance on non-renewable resources, lower operational costs, and bolster their environmental

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credentials. By witnessing tangible benefits like energy savings and enhanced crop yields, these growers become more inclined to invest in additional eco-friendly innovations. Over time, sustainability-focused practices not only preserve soil and water resources but also drive steady production gains, aligning with farmers' values and reinforcing their willingness to embrace future green technologies.

Equally critical is the presence of robust infrastructure encompassing reliable transportation networks, adequate storage facilities, and high-speed digital connectivity which dictates the pace and success of technology adoption. Access to fast internet enables farmers to leverage precision-agriculture tools, real-time data analytics, and online marketplaces for market intelligence and resource management. Well-maintained roads, efficient logistics, and modern warehousing reduce post-harvest losses by facilitating rapid movement of produce, supporting just-in-time harvesting and processing that maximizes freshness. Together, these infrastructural elements empower farmers to integrate advanced practices seamlessly, enhance operational efficiency, and expand their market reach while preserving product quality.

Workforce and Skills Dynamics

The workforce and skills dynamics play a dynamic role in farmers' ability to adopt agricultural innovations, with labor availability, skill levels, and flexibility directly influencing implementation success. A shortage of labor can hinder the adoption of modern methods and time-sensitive technologies, particularly in labor-intensive periods like planting and harvesting. Without sufficient workers, farmers may delay or avoid using advanced systems such as precision agriculture or automated harvesting. In such scenarios, the focus often shifts to automation as a substitute for human labor.

The skill level of available labor significantly affects how effectively new technologies are integrated into farming operations. Technically skilled workers enable more efficient use of tools, data analytics, and sustainable practices, which are essential as agriculture becomes increasingly digitized. A digitally competent workforce can enhance farm productivity and optimize resource use, maximizing the benefits of innovations like precision farming. On the other hand, unskilled labor may limit a farmer's ability to implement or fully utilize new technologies, reducing competitiveness in the market. Broader labor market dynamics, including migration patterns and generational attitudes, also shape innovation adoption. While younger workers tend to be more receptive to technology, older generations may resist change. Attracting youth to agriculture through education and outreach can lead to a tech-savvy labor force, but negative perceptions of farm work may deter interest and limit access to skilled labor unless those views are actively addressed.

Policy and Regulatory Support

A supportive policy and regulatory environment are crucial in fostering the adoption of agricultural innovations. Well-designed policies including financial incentives, subsidies, and research funding encourage farmers to invest in modern technologies such as precision farming tools, drones, and renewable energy systems. For instance, a government subsidy program in Penang aimed at promoting solar-powered irrigation could significantly reduce upfront costs and accelerate technology adoption. Government-sponsored research, especially when conducted in collaboration with local farmers, can result in context-specific solutions that address real agricultural challenges like pest resistance or climate adaptation. When farmers feel supported by these initiatives, they are more willing to experiment with and adopt innovative practices that enhance sustainability and productivity.

Equally important is the clarity and efficiency of the regulatory framework. Straightforward and supportive regulations can facilitate the rapid implementation of new technologies, while complex or overly restrictive rules can discourage innovation. Farmers are more likely to embrace change in a regulatory environment that allows for experimentation and minimizes bureaucratic hurdles. However, challenges such as bureaucratic delays, poor inter-agency coordination, and lack of farmer input in policymaking can become major barriers. For example, prolonged approval processes for installing modern equipment or stringent pesticide regulations without viable alternatives can lead farmers to avoid innovation altogether. When regulations are misaligned with on-the-ground realities, they not only delay progress but also erode trust in policy structures, ultimately hindering sustainable agricultural development.

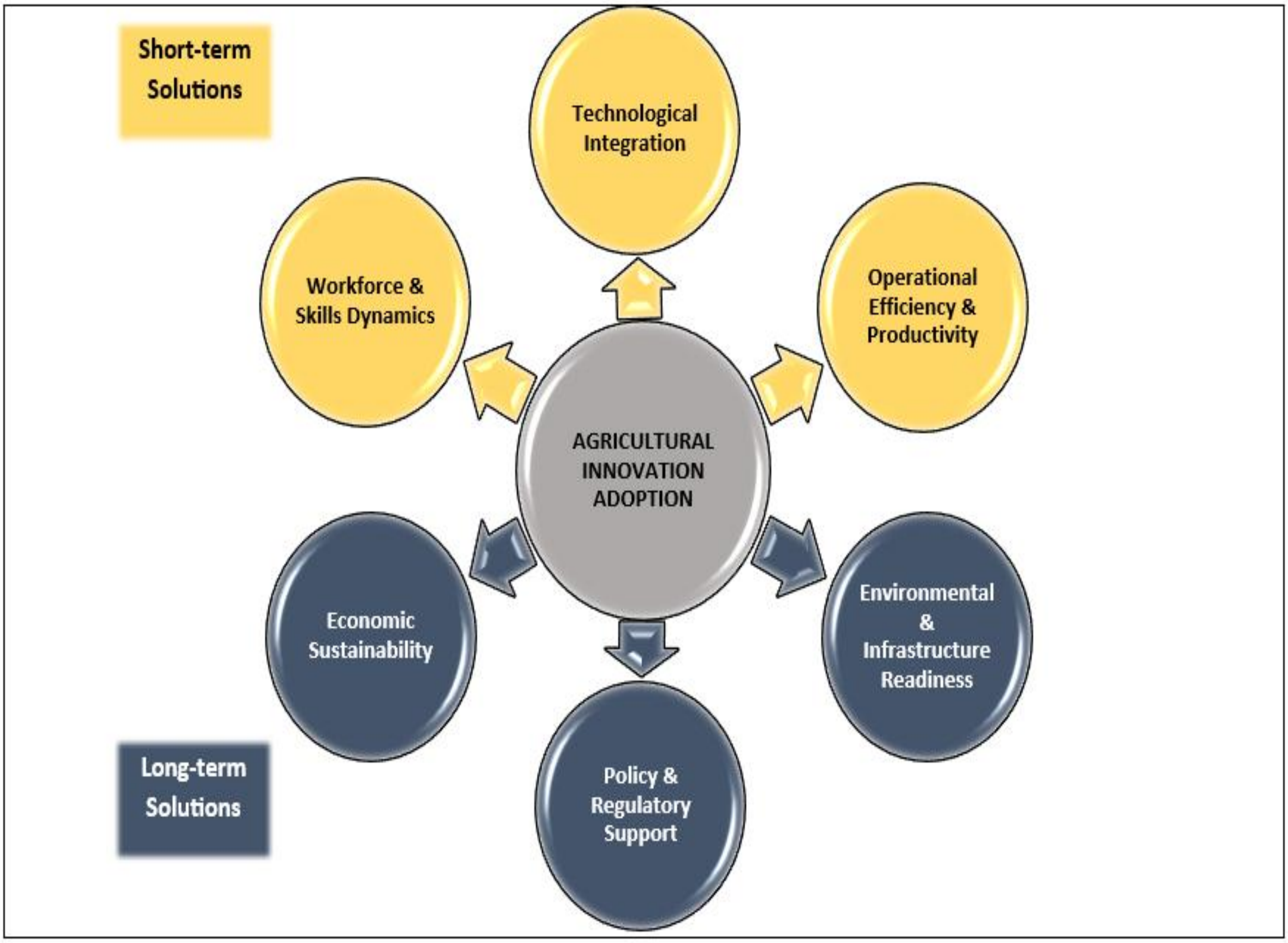

Figure 1 Framework for Agricultural Revolution and Management (FARM) Source: Shazanah & Norzanah (2024)

Validity and Reliability

Prolonged Engagement and Steadfast Observation

The study used strategies in line with qualitative best practices, particularly prolonged engagement and steadfast observation, to guarantee the validity of the research findings. Throughout the data collecting process, the researcher engaged with participants consistently also through follow ups in verifying the inputs provided during the interview sessions ensuring it is not misunderstood or misinterpreted. These exercises facilitated the growth of trust and a more thorough contextual knowledge of Penang farmers' reality. This prolonged engagement allowed the researcher to spot trends and clarify any unclear answers, guaranteeing the accuracy and comprehensiveness of the data.

Members Checking

The study employed member checking as a validation method to confirm six (6) key findings derived from interviews with farm operators at TKPM and Taman Agroteknologi Ara Kuda. This process took place during the seminar *Enhancing Farm Operations: Overcoming Barriers to Agricultural Innovations* on December 14, 2024, in Bukit Mertajam, Penang. The seminar allowed stakeholders including government officials, industry experts, and farmers to evaluate the findings based on their real-world experiences. The first confirmed theme, Workforce and Skills Dynamics, highlighted the gap in farmers' technical capabilities, which was widely acknowledged.

The Department of Agriculture and farmers alike emphasized the need for technical outreach, training, and demo farms. The second theme, Technological Integration, was validated through participants' preference for modular, adaptable solutions that allow gradual adoption. Companies like Vessel Pro and Vitrox

AgriTech showcased technologies tailored to diverse needs, aligning with farmers' desire for integration rather than total system overhauls. The third theme, Operational Efficiency and Productivity, focused on user-friendly tools that enhance farm performance without complicating operations. Farmers preferred plug-and-play solutions, as demonstrated by presentations from VF@RM and Vessel Pro. Real-world examples confirmed how basic IoT tools improved productivity. The fourth theme, Economic Sustainability, was also affirmed: both Agrobank and farmers stressed the difficulty of accessing affordable financing, reinforcing the need for grants and low-interest loans.

The fifth theme, Policy and Regulatory Support, drew consensus that current strategies often fail to consider local contexts. MARDI, FAMA, and the Department of Agriculture advocated for more flexible, localized policy frameworks and the formation of cooperatives.

Lastly, Environmental and Infrastructure Readiness was a major concern, with participants citing poor internet access, weak logistics, and lack of technical support as critical barriers. To address these, proposals were made to improve digital connectivity, upgrade roads, and enhance warehousing measures seen as essential for sustainable tech adoption in agriculture.

Peer Review

The study ensured dependability and credibility by integrating peer review throughout the data processing phase. Academic supervisors and peers rigorously examined the coding system comprising open, axial, and selective coding offering alternative perspectives that challenged assumptions and reinforced consistency in interpretation.

This peer engagement, along with thorough documentation of the coding process, supported both the reliability and traceability of analytical decisions. As part of the validation process, the Department of Agriculture Penang issued an official support letter dated March 6, 2025, endorsing collaboration with the researcher (Figure 2). This endorsement confirmed alignment between the research goals and departmental priorities, enhancing the study's credibility and confirming institutional trust in the findings' accuracy and practical relevance.

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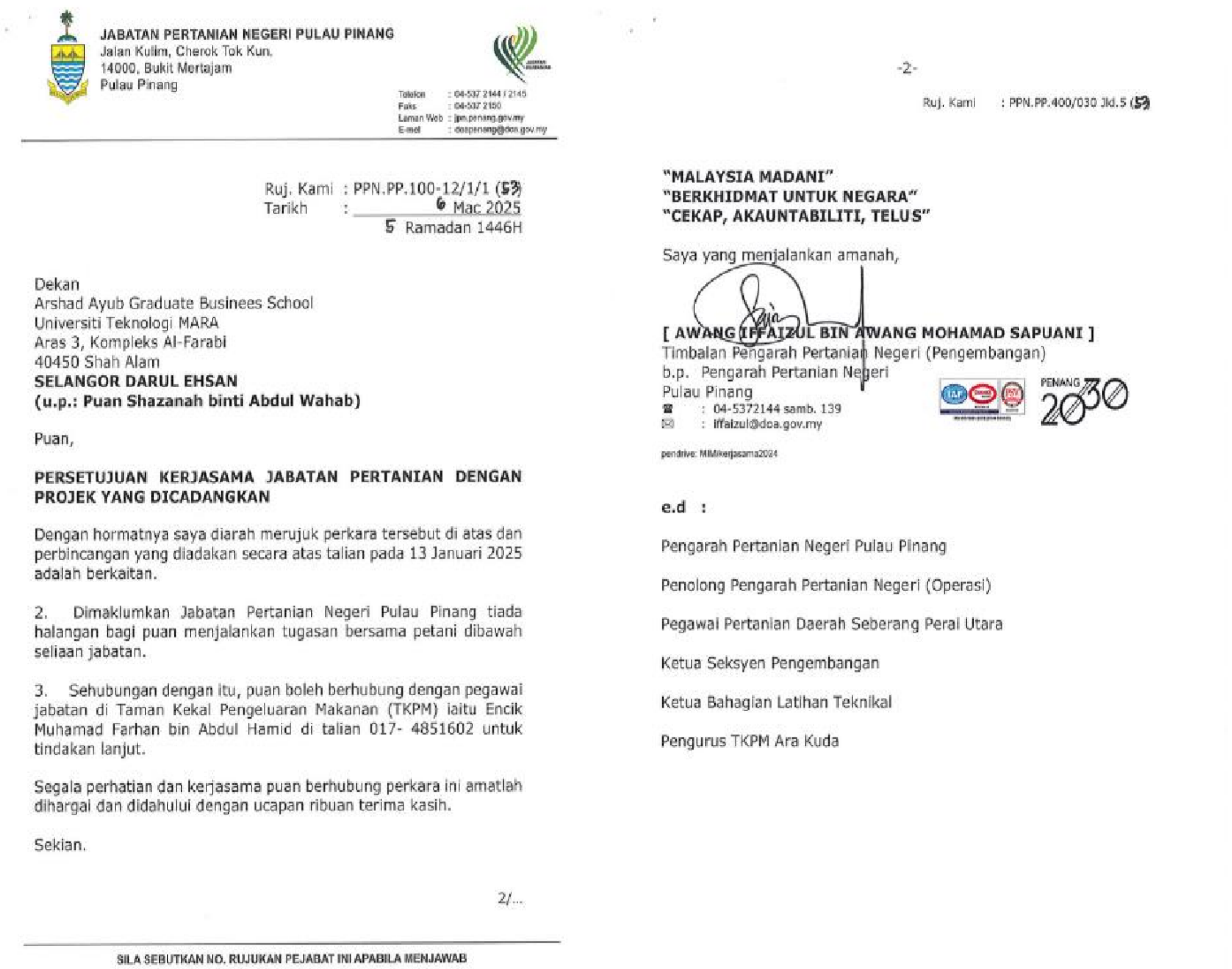

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Puan,

PERSETUJUAN KERJASAMA JABATAN PERTANIAN DENGAN PROJEK YANG DICADANGKAN

Dengan hormatnya saya diarah merujuk perkara tersebut di atas dan perbincangan yang diadakan secara atas talian pada 13 Januari 2025 adalah berkaitan.

2. Dimaklumkan Jabatan Pertanian Negeri Pulau Pinang tiada halangan bagi puan menjalankan tugasan bersama petani dibawah seliaan jabatan.

3. Sehubungan dengan itu, puan boleh berhubung dengan pegawai jabatan di Taman Kekal Pengeluaran Makanan (TKPM) iaitu Encik Muhamad Farhan bin Abdul Hamid di talian 017- 4851602 untuk tindakan lanjut.

Segala perhatian dan kerjasama puan berhubung perkara ini amatlah dihargai dan didahului dengan ucapan ribuan terima kasih.

Sekian.

2/...

SILA SEBUTKAN NO. RUJUKAN PEJABAT INI APABILA MENJAWAB

-2-

Ruj. Kami : PPN.PP.400/030 Jld.5 (53)

"MALAYSIA MADANI"
"BERKHIDMAT UNTUK NEGARA"
"CEKAP, AKAUNTABILITI, TELUS"

Saya yang menjalankan amanah,

[AWANG IFFAIZUL BIN AWANG MOHAMAD SAPUANI]
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s.k :

Pengarah Pertanian Negeri Pulau Pinang

Penolong Pengarah Pertanian Negeri (Operasi)

Pegawai Pertanian Daerah Seberang Perai Utara

Ketua Seksyen Pengembangan

Ketua Bahagian Latihan Teknikal

Pengurus TKPM Ara Kuda

Figure 2: Support Letter from Department of Agriculture Penang

To meet and exceed established qualitative standards, the study employed three key validation techniques: prolonged engagement and steadfast observation, member checking, and peer review surpassing Creswell's (2007) recommendation of two. According to Lincoln and Guba (1985), prolonged engagement builds trust and deepens understanding of the cultural and institutional context, which this study achieved through extended interaction with Penang farmers. Member checking, as emphasized by Merriam and Tisdell (2016), ensured that participants' perspectives were accurately represented. Peer review further supported reliability and confirmability by enabling external evaluation of coding and interpretation to identify potential biases and reinforce data-driven conclusions. Altogether, these methods validate the study as a trustworthy and contextually grounded contribution to understanding Human-AI integration and innovation in Penang's agricultural sector.

CONCLUSION

The study explores the complex relationship between human perceptions, attitudes, and the adoption of AI technology in agriculture, building upon existing innovation adoption models by incorporating key contextual factors like economic sustainability, technology integration, labor dynamics, and regulatory support. The findings demonstrate that integrating human-AI systems can significantly enhance agricultural productivity, efficiency, and sustainability, contributing toward achieving several Sustainable Development Goals (SDGs). By identifying specific drivers that influence innovation adoption such as trust, exposure, and technical capacity the research lays the groundwork for further inquiry and practical strategies aimed at scaling AI adoption in farming. It presents a comprehensive conceptual framework that combines human behavior with economic and policy factors, enhancing both theoretical understanding and practical application in agricultural innovation.

However, the study acknowledges limitations, primarily in terms of geographic scope and sample size. Since data was collected primarily from Penang, findings may not fully translate to regions with different agricultural systems or regulatory contexts. The relatively small number of qualitative participants may have also constrained the diversity of perspectives captured. Despite these limitations, the research offers valuable implications: theoretically, it deepens insight into how human trust, experience, and engagement with technology interact with broader environmental and institutional factors. Practically, it proposes actionable recommendations where farmers should engage in AI training, agribusinesses must ensure tools are user-friendly and supported, and policymakers are urged to create clear, supportive regulations and incentives for technology adoption. The study ultimately delivers a robust platform for enhancing AI integration in agriculture, aiming to drive future productivity, resilience, and sustainable development across the global agricultural sector.

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