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Bridging the technological divide in Malaysia's palm oil sector: Enhancing smallholder access to plantation-scale innovation

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***Abstract*---**Malaysia's palm oil industry plays a vital role in the global edible oil market, driven by both large plantations and over 440,000 smallholders who cultivate around 40% of the country's total oil palm area. While large plantations have adopted precision agriculture, mechanized harvesting, and advanced crop monitoring systems, independent smallholders often lack access to such innovations, leading to significant productivity disparities. This technological gap not only hampers national output but also entrenches economic inequality within the sector. To address this, there is an urgent need to identify plantation-level technologies suitable for smallholder adoption and to understand the drivers that influence their readiness to adopt these technologies. This study aims to identify the technologies employed by large oil palm plantations that have the potential to be adopted by smallholders. The findings from this review are expected to inform inclusive technology integration strategies in Malaysia's palm oil sector and provide evidence-based insights into bridging the productivity gap between plantations and small farms.

***Keywords*---**oil palm, Malaysia, technology, smallholders, SLR, plantation.
JEL Classification: O33, Q16, Q12, O13

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INTRODUCTION

Malaysia is one of the world's leading palm oil producers, contributing significantly to the global supply. In 2021 alone, Malaysia produced approximately 18 million tons of Crude Palm Oil (CPO), with exports totalling around 15 million tons (Parveez et al., 2022). This impressive output is driven by a combination of large-scale plantations, government-linked schemes, and a substantial number of smallholders. Multinational corporations such as Sime Darby Plantation and IOI Corporation manage vast plantation areas using modern technologies and sustainable practices, setting benchmarks for efficiency and productivity.

Smallholders, however, are a vital yet vulnerable part of this ecosystem. Comprising about 40% of the total palm oil production area in Malaysia, the country is home to around 440,000 smallholders (Solidaridad Network, 2022). These smallholders, cultivating oil palm typically on plots under 40 hectares, can be classified as either organized (receiving institutional support) or independent (operating without formal assistance). While organized smallholders benefit from resources and guidance from entities like FELDA or private firms, independent smallholders face numerous barriers including limited access to finance, poor farm management, low yields, land tenure challenges, and a lack of technological adoption. On average, smallholders produce 14-18 tons of Fresh Fruit Bunches (FFB) per hectare, significantly lower than the 18–22 tons achieved by larger plantations (Ishak & Manaf, 2020).

The disparity in productivity between plantations and smallholders is largely attributed to technological gaps. Plantations typically employ advanced tools and practices such as precision agriculture, sensor-based monitoring, mechanized harvesting, and improved seed varieties. These tools enhance yield, reduce waste, and improve crop health through data-driven decision-making. Conversely, smallholders, especially independent ones, struggle to afford or access these innovations. Their reliance on manual labor, limited knowledge of best practices, and insufficient training restricts their ability to increase yields or operate sustainably. These constraints have broader implications for the palm oil sector, limiting national productivity and reinforcing income inequality between large producers and smallholders.

One promising solution is the adaptation of plantation level technologies for smallholder use. However, simply transferring technology is not enough. It is crucial to first identify suitable technologies, assess the factors influencing adoption, and evaluate smallholders' readiness to adopt these technologies. Among these factors, both push factors such as training, subsidies, and institutional support and pull factors like perceived benefits, profitability, and market incentives play a critical role in shaping adoption decisions. Understanding how these drivers vary, particularly between organized and independent smallholders, is essential for designing effective and inclusive technology interventions.

Despite growing academic interest in technology use within the oil palm industry, current efforts are often limited to narrative or traditional literature reviews, which are susceptible to bias and lack transparency in study selection (Shaffril et al., 2020). These issues make it difficult to replicate or validate previous findings. There is a clear need for a systematic literature review (SLR) to rigorously synthesize the available evidence on technology adoption among oil palm smallholders.

Building on this context, this study is guided by two central research questions:

1. What types of technologies are currently employed by large oil palm plantations across various stages of production, from planting to postharvest handling?
2. What are the key factors that influence independent smallholders' readiness and willingness to adopt these plantation level technologies in Malaysia?

The primary objective of this study is to identify and document the technologies utilized by large oil palm plantations at different stages of crop production, including planting, crop management (such as fertilization, pest and disease control, and pruning), harvesting, in-field transportation, and postharvest handling. The secondary objective is to investigate the factors, both enabling and constraining, that affect independent smallholders' willingness and preparedness to adopt these technologies. Through this, the study aims to support more inclusive technological integration in Malaysia's palm oil sector and contribute to narrowing the productivity gap between plantations and smallholders.

METHODOLOGY

A Systematic Literature Review (SLR) will be conducted to uncover key push and pull factors influencing technological adoption and smallholder readiness for both organized and independent to implement innovations. To ensure transparency, reproducibility, and methodological rigor, this study will adhere to the ROSES (RepOrting standards for Systematic Evidence Syntheses) framework, a tailored approach for environmental systematic reviews and systematic maps, developed by Haddaway et al. (2018).

ROSES

The integration of ROSES enhances methodological transparency and rigor through several key components. A pro forma checklist is completed at both the protocol and final report stages to ensure systematic documentation of the search strategy, eligibility criteria, screening procedures, data extraction, and quality appraisal. A ROSES-compliant flow diagram is used to trace each stage of the study selection process, from initial identification to final inclusion. Additionally, a descriptive metadata summary is provided, detailing elements such as databases searched, search timelines, synthesis methods, and quality appraisal tools to enable clear methodological assessment and reproducibility.

Search Strategy

Synonyms, related phrases, and variations of the main keywords are searched during the identification phase of the SLR to ensure comprehensive coverage of relevant literature. The basis for keyword generation is the study topic. Many relevant studies were discovered by searching Web of Science and Scopus. Information regarding the search strategy is contained in the exact search term that is entered into each database.

Search String

Table 1: The search string

Databases	**Search string**
Scopus	TITLE-ABS-KEY ((“oil palm" OR "palm oil")) AND ("technology adoption”) OR (“readiness") OR ("acceptance") OR ("implementation") OR (“existing”) AND ("agricultural technology") AND (“bridging the gap" OR "smallholder*" AND "large plantations*"))
Web of Science (WOS)	TITLE-ABS-KEY ((“oil palm" OR "palm oil")) AND ("technology adoption”) OR (“readiness") OR ("acceptance") OR ("implementation") OR (“existing”) AND ("agricultural technology") AND (“bridging the gap" OR "smallholder*" AND "large plantations*"))

Screening

Table 2: The inclusion and exclusion criteria

Criteria	**Inclusion**	**Exclusion**
Document Type	Article Journal	Article review
Language	English	Non-English
Regions	Global	None

A comprehensive literature analysis was done by looking up key phrases in the SCOPUS and WOS databases. At first, these keywords were used to find more than 20,000 papers. Nevertheless, after using inclusion and exclusion criteria, we reduced the number of publications in our selection to 100 that were especially relevant to our study. About 62 of these papers were used in this systematic literature review paper.

Screening results

Table 3: Screening Results

Databases	**Number of articles**	**Inclusion**	**Exclusion**
SCOPUS	**42**	articles discuss the technologies used and the factors driving their	articles don't address the technologies or factors affecting the technological

		adoption in the palm oil sector	implementation
WOS	**20**	articles discuss the technologies used and the factors driving their adoption in the palm oil sector	articles don't address the technologies or factors affecting the technological implementation

By adhering to these criteria, the study ensures that the selected 62 articles are pertinent and contribute valuable insights into the technologies used in oil palm plantations. Following the initial screening and selection of relevant studies, the study identified specific sub-themes and broader themes to address the study's objectives. Through a detailed review of the selected literature, we identified 28 sub-themes and grouped them into 10 main themes. These themes and sub-themes provide a structured framework for understanding the technological landscape in oil palm plantations. The themes explored include precision agriculture, smart irrigation system, socioeconomic factors, technology compatibility, technology acceptance, government support & policies, training & education support and agricultural innovations.

The selection process is summarized in Figure 1 using the ROSES flow diagram, which outlines the identification, screening, and inclusion stages.

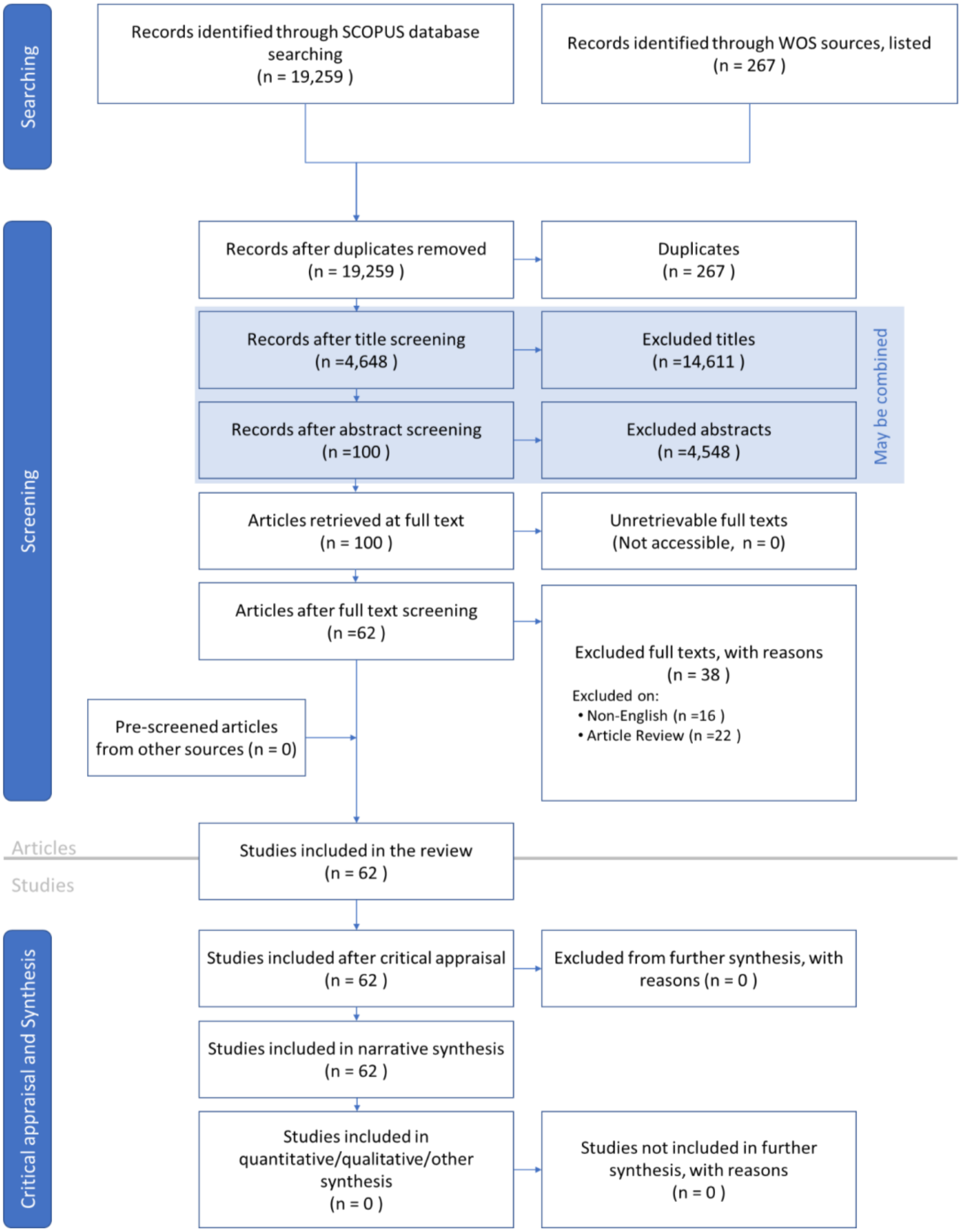

Figure 2: ROSES flow diagram

RESULTS AND DISCUSSION

The summary of the identified themes and sub-themes is as follows:

RESEARCH OBJECTIVE	THEME	SUBTHEME	AUTHOR(S)	✓
RO1: Technologies used in large plantations that can be adopted by smallholders	Precision agriculture	Internet of things (IoT) in agriculture	Roslee et al. (2024), Ruslan et al. (2024), Culman et al. (2023), Saleh et al. (2023)	✓
		Smart sensors and data analytics	Santoso et al. (2024), Yamin et al. (2022), Khan et al. (2022), Mohad et al. (2021), Khorramnia et al. (2014), Azmi et al. (2020), Warid & Asrol (2022), Asrol et al. (2023), Samseemoung et al. (2011), Shaharum et al. (2020), Parveez et al. (2022)	✓
	Smart irrigation system	Perception and adoption of smart irrigation technologies	Chalvantharan et al. (2023), Manorama et al. (2021),	✓
	Labour-saving technologies		Mohamad et al. (2023), Robins (2018)	✓
	Ecological pest management	Biological control	Puan et al. (2020), Zainal Abidin et al. (2021), Tohiran et al. (2024), Mulyana et al. (2020), Primananda et al. (2024), Omar et al. (2016), Budihardjo et al. (2019), Verwilghen (2023),	
		Biodiversity and habitat complexity	Yahya et al. (2016), Chenon and Susanto (2023)	
RO2: Factors affecting the adoption of technology among independent smallholders	Socio-institutional factors and farmer participation	Adoption behavior	Yaseen et al. (2023),	
		Social networks and peer influence	Rizal et al. (2023), Besar et al. (2020)	✓
	Institutional support	Technology transfer and capacity building	Ampofo et al. (2024), Raharja et al. (2020), Anwar et al. (2021)	✓
		Institutional development and policy evolution	Syahza and Asmit (2020), Corciolani et al. (2019), Astari et al. (2025)	✓

	Technology compatibility	Organizational and environmental context	Parvand and Rasiah (2021), Chong Tan and Ndubisi (2014), Parvand (2021)	✓
	Technology acceptance	Perception and attitude towards technology	Diana and Farida (2023), Martínez-Arteaga et al. (2023), Aguilar-Gallegos et al. (2015)	✓
		Perceived usefulness	Ruiz et al. (2017), Adnan et al. (2022), Adejuwon et al. (2014), Rangel et al. (2014)	✓
	Government support & policies	Certification and standards for smallholders	Hamid et al. (2024), Martin et al. (2015), Dewi et al. (2023), Pramudya et al. (2022), Wibowo et al. (2023)	✓
		Stakeholders' management	Raharja et al. (2020)	✓
		Policy frameworks and incentives	Yuslaini et al. (2023), Rudolf et al. (2020), Brenneis et al. (2023), Adejuwon et al. (2016) Euler et al. (2016), Zhao et al. (2023)	✓
	Training & education support	Technical assistance and training	Adeniyi et al. (2019), Abdullah et al. (2024)	✓

Precision Agriculture

Precision agriculture technologies, particularly those driven by the Internet of Things (IoT), have become increasingly vital for enhancing productivity among smallholder oil palm farmers. These tools support accurate, real-time decision-making in resource-constrained environments by enabling targeted management of water, soil, and crop health. For example, Roslee et al. (2024) developed an IoT-based monitoring algorithm that leverages the LoRaWAN protocol to connect field sensors with gateways and a central server. This low-power, low-bitrate wireless system enables real-time monitoring of soil conditions in peatland plantations, offering a cost-effective and energy-efficient solution for water management. Their system has demonstrated significant improvements in precision water control, making it both practical and scalable for smallholder implementation.

Similarly, Ruslan et al. (2024) designed a prototype soil monitoring system using LoRa technology, integrating multiple sensors to measure soil moisture, temperature, and environmental conditions. The system operates with low energy consumption and transmits data wirelessly over long distances, making it suitable for smallholders in rural or remote areas. Their findings confirm the feasibility and affordability of deploying IoT solutions to assist small-scale farmers in monitoring critical soil parameters without relying on labor-intensive practices.

Together, these studies highlight how IoT-enabled precision agriculture can empower smallholders with data-driven tools that improve productivity, conserve resources, and support long-term sustainability in oil palm cultivation.

Beyond soil and water management, IoT-based precision agriculture has also shown promise in supporting nutrient deficiency detection and crop health monitoring, which are equally critical for improving yield outcomes among smallholders. For instance, Culman et al. (2023) developed a novel IoT application that combines sensor networks with imaging tools to identify macro- and micronutrient deficiencies in oil palm trees. The system provides automated, real-time diagnostics, enabling farmers to apply fertilizers more accurately and efficiently. This not only helps reduce input waste but also minimizes the environmental impact of over-fertilization, which is often a challenge in small-scale operations with limited technical support.

Likewise, Saleh et al. (2023) implemented a real-time soil monitoring system using LoRa communication, equipped with sensors that measure temperature, pH, and moisture content. Data is transmitted wirelessly to cloud-based platforms like ThingSpeak, where farmers can remotely monitor and respond to changes in soil conditions. This integration of IoT and cloud computing supports timely decision-making and reduces dependence on manual field checks, which are often impractical for smallholders managing multiple plots or working in geographically isolated areas.

In addition to IoT-based soil and water monitoring, smart sensors and data analytics are increasingly being utilized in oil palm plantations to support disease detection, nutrient assessment, and overall yield improvement. These technologies contribute to more informed, site-specific decision-making by combining sensing hardware with advanced analytical models.

One key area of application is disease and nutrient management. Santoso et al. (2024) demonstrated the integration of remote sensing and machine learning to detect Basal Stem Rot (BSR) and assess leaf nutrient levels in oil palm trees. By using a UAV-mounted multispectral camera, their system effectively distinguished between healthy and infected trees, offering a practical solution for early detection and plantation health monitoring. Similarly, Khorramnia et al. (2014) evaluated the use of optical sensor systems to estimate nutrient deficiencies in oil palm leaflets. Their study, which analyzed data from 164 trees across three Malaysian farms, showed that support vector machine (SVM) and artificial neural network (ANN) models could predict essential nutrient levels, including nitrogen, phosphorus, potassium, magnesium, calcium, and boron with accuracies ranging from 59% to 85%. These findings support the potential of sensor-based diagnostics to enable more efficient fertilization strategies and reduce nutrient waste.

Beyond diagnostics, data analytics is increasingly used for yield prediction and agronomic planning. Khan et al. (2022) utilized machine learning (ML) models to predict oil palm yields based on 12 environmental variables, including rainfall, temperature, and soil moisture, over a dataset spanning 420 months. Their analysis identified rainfall frequency, root-zone soil moisture, and temperature as the most influential factors in predicting yield.

Smart sensor applications have also extended to precision soil management. Mohad et al. (2021) implemented on-the-go electrical conductivity (EC) sensors mounted on an autopilot tractor to map soil conductivity at a Malaysian oil palm plantation. The generated spatial data was then used to create GIS-based maps, which facilitated more precise soil management strategies. In another study, Yamin et al. (2022) developed a variable-rate fertilizer applicator that simultaneously applies nitrogen, phosphorus, and potassium. This applicator adjusts rates based on real-time soil nutrient readings and uses flow control with finite element analysis to ensure optimal nutrient distribution. These innovations highlight the synergy between sensor technologies and analytics in enhancing site-specific soil and nutrient management.

Furthermore, precision technologies have been adopted to improve harvest quality and operational efficiency. Azmi et al. (2020) assessed autonomous tractor steering systems and found that these systems enhance energy use, field accuracy, and operational capacity in oil palm plantations. In the area of harvest optimization, Asrol et al. (2023) applied the YOLOv4 deep learning model to evaluate oil palm fruit ripeness using real-time video captured on smartphones. The system achieved high accuracy and usability even on mobile devices, making it practical for smallholder applications. Complementary to this, Samseemoung et al. (2011) used drone-mounted imaging and chlorophyll analysis to detect upper stem rot and other pest-related stress in both young and mature palms, indicating the broader application of remote sensing in early pest and disease detection.

Smart sensing and data analytics are also contributing to sustainability assessment and land-use planning. Shaharum et al. (2020) employed Google Earth Engine and machine learning techniques to map oil palm land cover across Peninsular Malaysia with high classification accuracy. In a related study, Warid and Asrol (2022) used GIS-based indicators to assess oil palm sustainability performance in Sumatra and Borneo, focusing on biodiversity, land use change, and greenhouse gas emissions. These assessments underscore the sector's growing emphasis on environmental accountability. Complementing these efforts, Parveez et al. (2022) discussed next-generation innovations such as AI-driven yield forecasting, tree navigation systems, and bioproduct generation from biomass, further positioning smart agriculture as a foundation for future sustainability in the oil palm sector.

Smart Irrigation System

Smart irrigation systems have been increasingly adopted in oil palm plantations as part of broader efforts to integrate precision agriculture technologies. These systems aim to improve water use efficiency through automated controls, sensor networks, and data-driven irrigation scheduling. Chalvantharan et al. (2023) reported that the implementation of smart irrigation systems can enhance productivity and profitability while reducing water usage, contributing to improved plant growth. Similarly, Manorama et al. (2021) investigated the effects of mulching and resource management in irrigated oil palm fields and found a notable increase in soil organic carbon (SOC) content. The results suggest that improved water and soil practices can contribute to long-term soil health in oil palm systems.

Labor-saving technologies

Labor-saving technologies play a critical role in addressing the physical demands of oil palm harvesting, a process that remains largely manual in many plantations. In particular, ergonomic interventions have been explored to improve worker welfare and reduce the risk of injury. Mohamad et al. (2023) developed a structural design for a passive wearable exoskeleton intended to assist harvesters during oil palm cutting operations. The exoskeleton was designed to reduce muscle fatigue and physical strain, particularly in the upper body, which is heavily engaged during repetitive harvesting motions. Their design integrated structural analysis, anthropometric considerations, and user comfort, aiming to increase worker endurance and productivity while minimizing the risk of musculoskeletal disorders. The study highlighted the potential of wearable assistive devices as a cost-effective solution in plantations where full mechanization is not feasible due to terrain or cost constraints.

The search for labor-saving solutions in the oil palm sector is not new. Robins (2018) provided a historical account of smallholder efforts to mechanize palm oil production in West Africa between 1850 and 1950. During this period, smallholders experimented with imported machines and locally adapted tools to reduce the manual workload associated with fruit processing and oil extraction. While many of these early technologies were only partially successful or faced resistance due to maintenance issues, Robins' analysis highlights the long-standing relevance of technological innovation in alleviating labor intensity in palm oil production. This historical context reinforces the ongoing relevance of developing and adopting appropriate labor-saving innovations for smallholder and plantation settings alike.

Ecological Pest Management

Biological pest control has emerged as a key strategy for reducing dependency on chemical rodenticides in oil palm plantations. One widely adopted method involves the introduction of barn owls (Tyto alba) as natural predators of rats, a major pest in oil palm cultivation. Puan et al. (2020) found that barn owls preyed opportunistically on various rat species without strong predation preference, suggesting a broad but non-targeted suppression effect. While promising, the findings underscore the need to complement owl-based control with additional strategies to optimize pest management outcomes.

Subsequent studies expanded on this approach. Zainal Abidin et al. (2021) compared barn owl deployment with conventional rodenticide use and found that both methods reduced rat activity, but barn owls posed fewer ecological risks. The study emphasized the importance of artificial nest boxes in supporting owl populations while also cautioning that long-term success depends on continued ecological maintenance and monitoring. Reinforcing this, Omar et al. (2016)

warned that rodenticide exposure could harm barn owl nestlings, highlighting potential trade-offs when chemical and biological methods are used simultaneously.

Tohiran et al. (2024) introduced a complementary avian-based method using artificial hunting perches to attract raptors, including owls, hawks, and nightjars. This low-cost intervention enhanced predator activity and diversified the assemblage of natural enemies in oil palm landscapes. Similarly, Mulyana et al. (2020) demonstrated that Sulawesi Masked-owls (Tyto rosenbergii) successfully bred in artificial nest boxes within plantation settings, supporting the long-term establishment of predatory bird populations.

A decade-long study by Primananda et al. (2024) further validated the ecological and operational benefits of barn owl integration. In a Central Kalimantan plantation spanning 80,000 hectares, the barn owl population expanded significantly, with a 75 percent nest box occupancy rate recorded by 2022. Rat damage declined below the 5 percent threshold and chemical baiting was eliminated entirely. These outcomes reinforce the potential for well-managed biological control to replace chemical interventions at scale. Beyond pest suppression, Budihardjo et al. (2019) linked barn owl activity to reductions in parthenocarpy and fruit malformation in fresh fruit bunches (FFBs), suggesting a positive impact on crop quality and economic returns. This broadens the scope of biological control from pest mitigation to production enhancement.

A comparative assessment by Verwilghen (2023) of predator communities in Indonesian plantations practicing ecological versus conventional rodent control revealed that biodiversity-friendly systems characterized by habitat complexity and nest box installation hosted higher predator abundance and achieved better rodent suppression than chemically managed sites. These findings further support the adoption of integrated ecological strategies to enhance sustainability and biodiversity conservation in oil palm plantations.Beyond targeted biological control measures, maintaining biodiversity and habitat complexity in oil palm landscapes plays a vital role in enhancing natural pest regulation. Chenon and Susanto (2023) conducted ecological observations on diurnal bird species within Indonesian oil palm plantations. Their study documented a wide range of bird taxa and emphasized that oil palm landscapes, despite being monocultures, can support notable avian biodiversity when certain ecological features are present.

These observations align with Yahya et al. (2016) in demonstrating that both nocturnal and diurnal bird communities respond positively to increased habitat complexity. The presence of vegetation corridors, varied canopy structures, and minimal chemical disturbance were identified as contributing factors to bird abundance and diversity. Together, these studies reinforce the idea that enhancing structural and ecological heterogeneity in oil palm plantations not only supports broader biodiversity conservation goals but also has the potential to contribute to ecosystem services such as pest control. This highlights the importance of integrating biodiversity-friendly design principles into plantation management practices.

Socio-Institutional Factors and Farmer Participation

Understanding the social and behavioral dynamics behind farmers' decision-making is critical to promoting sustainable practices and technology adoption in the oil palm sector. Yaseen et al. (2023) investigated the adoption and non-adoption of oil palm cultivation among smallholders in Northeast Thailand. Their findings highlighted a range of decision-making factors, including land suitability, perceived profitability, risk aversion, and access to agricultural knowledge and institutional support. While adopters were motivated by economic incentives and perceived benefits, non-adopters cited concerns about land degradation, uncertain returns, and inadequate information. Both studies underscore that farmers' choices are not made in isolation but are the result of complex social, economic, and institutional interactions. Recognizing these behavioral and contextual drivers is essential for designing inclusive agricultural interventions that resonate with smallholder realities.

In addition to individual-level decision-making, broader socio-institutional factors such as social capital and structural support systems play a vital role in shaping smallholder participation in sustainable oil palm practices. Rizal et al. (2023) found that smallholders' involvement in certification schemes like the Malaysian Sustainable Palm Oil (MSPO) and the Roundtable on Sustainable Palm Oil (RSPO) was heavily influenced by community-based communication networks and a shared group identity. These social dynamics facilitated the diffusion of sustainability-related knowledge and practices, indicating that strong social capital can accelerate collective adoption. Expanding on this, Besar et al. (2020) investigated the key challenges experienced by smallholders in Terengganu, Malaysia. The study identified barriers such as limited access to modern technologies, volatile market prices, pest infestations, and chronic labor shortages. These constraints hindered both productivity and participation in sustainable initiatives. The authors recommended tailored policy interventions, including advisory support, financial subsidies, and farmer training, to improve smallholders' capacity to adopt sustainable and efficient farming practices. Together, these studies emphasize that fostering farmer participation requires not only technical solutions but also attention to social cohesion, institutional accessibility, and economic stability.

Institutional Support

Institutional support plays a central role in promoting the adoption of sustainable agricultural practices, particularly through mechanisms such as technology transfer and capacity building. Ampofo et al. (2024) investigated the factors influencing the uptake of sustainable oil palm practices across six major producing regions in Ghana. Their study emphasized the importance of institutional networks, extension services, and professional associations in shaping farmers' decisions to adopt improved seeds, fertilizers, pest management strategies, and conservation techniques. While formal institutions were more effective in promoting natural resource management than input-intensive technologies, the findings highlight the need for an integrated institutional approach that leverages both formal and informal support structures. Similarly, Raharja et al. (2020) developed an institutional strengthening model for independent smallholders in Riau and Jambi, Indonesia. Their model focused on improving access to technology by enhancing the roles of cooperatives, corporate partnerships, and farmer associations. By encouraging collaboration among government agencies, mills, financial institutions, and input providers, the model aims to build institutional capacity that enables smallholders to adopt modern agricultural technologies more effectively.

Anwar et al. (2021) also explored institutional strategies for enhancing smallholder capacity in Indonesia, highlighting the role of cooperatives, partnerships with processing mills, and collaborative governance frameworks in improving access to technical knowledge, inputs, and markets. These organizational structures were shown to be instrumental in overcoming the constraints that often limit smallholder participation in sustainable palm oil production. Their findings reinforce the argument that institutional coordination and local-level planning are essential to equipping smallholders with the skills and resources necessary for long-term sustainability.

Beyond individual-level capacity building, the broader development of institutional frameworks and policy environments is essential for supporting sustainable transitions in the oil palm sector. Syahza and Asmit (2020) examined how institutional arrangements can stimulate downstream oil palm industry development in Riau Province, Indonesia. Their study considered six critical areas, including regional capacity, employment potential, environmental considerations, economic multiplier effects, and strategic production zones. Findings revealed that oil palm expansion, when backed by appropriate institutional and infrastructural support, significantly boosts rural economies, generates inclusive growth, and enhances household livelihoods. The authors emphasized the importance of eco-friendly institutional strategies that align environmental sustainability with economic empowerment goals.

Adding a global dimension, Corciolani et al. (2019) analyzed how contested narratives around palm oil legitimacy influence institutional responses across both producing and consuming countries. Their study of international media coverage demonstrated how palm oil is alternatively framed as either a contributor to economic development or a source of social and environmental harm. These discourses affect the legitimacy of palm oil institutions and influence how sustainability policies are shaped and received. The study highlights that institutional support is not limited to technical and regulatory actions, it also involves shaping public perceptions and normative frameworks that underpin policy success.

Astari et al. (2025) applied a historical institutionalism lens to analyze the evolution of Indonesia's palm oil governance. They argued that institutional legacies, such as past policy decisions, stakeholder power dynamics, and governance structures which have created path dependencies that continue to influence the effectiveness of current institutional reforms. Understanding these historical trajectories is crucial for developing policies that are not only technically sound but also contextually grounded in the institutional realities of the palm oil sector. Their work underscores that sustainable transformation requires adaptive institutional design informed by both present-day challenges and long-standing governance patterns.

Technology Compatibility

The successful adoption of advanced technologies in the palm oil sector often depends on how well these innovations align with existing organizational, environmental, and technological contexts. Parvand and Rasiah (2021) examine this dynamic within palm oil milling firms in Malaysia, highlighting the critical role of technology attributes such as relative advantage, compatibility, complexity, and observability in influencing adoption decisions. Their study also considers environmental and organizational factors that shape firms' readiness and capacity to integrate new technologies effectively. This comprehensive approach emphasizes that technology compatibility is not solely about technical fit but also about aligning innovations with broader organizational and environmental conditions to ensure sustainable uptake and performance improvements.

Supply chain relationships and organizational resources are key enablers of technological innovation and overall enterprise performance in the palm oil processing sector. Chong Tan and Ndubisi (2014) examine these interconnections across Asian palm oil processing firms, finding that firms with higher-quality supply chain relationships demonstrate greater capacity for technological innovation. Their study highlights that trust, communication, and collaboration among supply chain partners significantly enhance the effective adoption of new technologies. Additionally, organizational resources such as skilled personnel, financial assets, and technological infrastructure were shown to directly impact firms' innovation performance. These factors collectively contribute to improved operational efficiency, product quality, and competitive advantage in the palm oil processing industry.

The technological capability of palm oil mills plays a crucial role in determining the success of technology adoption and overall firm performance. Parvand (2021) examines this dynamic in Malaysian palm oil mills, revealing that firms with well-developed technological capabilities including skilled personnel, technical knowledge, and adequate infrastructure achieve higher operational efficiency and improved financial outcomes. This capability not only facilitates the integration of advanced technologies but also enhances a firm's flexibility and competitiveness in a rapidly evolving industry. These findings highlight the importance of developing and maintaining strong technological competencies to ensure sustainable innovation and business success in the palm oil sector.

Technology Acceptance

A growing body of literature reveals that smallholders' acceptance of technology in the oil palm sector remains uneven and often limited by socioeconomic, institutional, and contextual barriers. Studies across several countries indicated that while larger plantations tend to adopt advanced technologies readily, smallholders are generally more hesitant, preferring tools that are free, simple, and require minimal technical expertise.

Diana and Farida (2023) investigated the use of remote sensing technology in Indonesia's oil palm farms, covering state-owned, private, and smallholder operations. Their study found that while private and state-owned plantations showed strong positive attitudes toward remote sensing, 60% of smallholders opposed it. Smallholders tend to adopt technologies that are free and easy to use. The authors emphasize the importance of user retention, alongside the need for academia and government to engage in extensive socialization and policy dissemination. Remote sensing technology offers social benefits such as reducing labor requirements and improving profitability and efficiency, ultimately empowering people and the environment and boosting corporate revenues.

In Mexico, although oil palm cultivation has expanded significantly, yields remain below potential due to limited adoption of new technologies. Aguilar-Gallegos et al. (2015) identified three adoption categories: advanced adopters focus on plantation health, grower associations, and production management; intermediate adopters prioritize plant nutrition, harvest, and genetics. The study recommends encouraging collaboration and tailoring extension services to enhance technology acceptance and economic gains in the oil palm sector.

Adnan et al. (2022) studied ICT adoption among Malaysian oil palm settlers, developing a conceptual framework based on technological and demographic factors, supported by Rogers' diffusion of innovation theory. The study found a positive correlation between technology and ICT use, with 84.4% of respondents being men and a high adoption rate of 65.4%. This framework could underpin future agricultural digitalization efforts. Adejuwon et al. (2014) highlighted that small-scale oil palm fruit processing in Nigeria largely remains traditional, with limited uptake of processing technologies. Their innovation systems analysis revealed a split between formal and informal sectors. Although institutions like the Nigerian Institute for Oil Palm Research have developed processing methods for all five palm oil production stages, widespread use remains limited. The study advocates enhancing technology adoption via both science-based and experiential innovation approaches and fostering stronger collaboration between fabricators and processors.

In Colombia's Tibu municipality, strategic alliances supported by USAID and the government have played a key role in strengthening small and medium-sized oil palm growers, contributing positively to the local economy. Despite these efforts, productivity levels remain inconsistent across producers. A 2013 survey revealed that 72.6% of plantations had adopted general technologies aimed at improving soil characterization, topography, soil preparation, and drainage system design (Rangel et al., 2014). Building on this, Ruiz et al. (2017) employed the Technology Balance Index (TBI) to assess yield gaps among similar farm categories, identifying appropriate planting, harvesting, and nutrition practices as major drivers of technology adoption and key factors in narrowing production disparities. Complementing these findings, Martínez-Arteaga et al. (2023) examined the use of irrigation technology in oil palm plantations and found adoption rates below 15%. They reported that uptake was significantly shaped by factors such as grower age, plantation size, and access to extension services, underscoring the need for more targeted outreach and farmer support mechanisms.

Government Support and Policies

As the Malaysian palm oil industry expands rapidly, it faces social, environmental, and sustainability challenges. While technologies exist to balance rural economic development with environmental conservation, their adoption, particularly among smallholders, has been limited. Interviews with 38 smallholders highlighted barriers to sustainable investment, including restricted access to global market knowledge, corruption, legal title uncertainty, low economic status, and social marginalization. These factors contribute to broader theoretical discussions on innovation and investment within marginalized communities (Martin et al., 2015). Malaysia's oil palm sector is vital to the nation's GDP, foreign exchange earnings, and employment. The government mandated MSPO certification by 2020, which aims to help farmers and smallholders reduce waste, increase palm oil sales, and overcome operational challenges. The certification also promotes improved agricultural practices, social development, and climate change adaptation (Hamid et al., 2024).

Similarly, in Indonesia, adoption of the Indonesian Sustainable Palm Oil (ISPO) standard among smallholders remains poor. Dewi et al. (2023) identify key factors for successful ISPO implementation including clear benefits, guidance, financial support, partnerships, stakeholder responsibilities, human resources, and legal clarity. They conclude that government policies should focus on supporting human resources, capital, agricultural management, and marketing capabilities. A qualitative study highlights that the slow implementation of ISPO accreditation is due to complex regulations and limited capacity among smallholders. The study recommends incentives such as financing, regulatory measures, technical assistance, promotion, and awards for best practices to accelerate ISPO adoption and improve market access (Pramudya et al., 2022).

Likewise, the Roundtable on Sustainable Palm Oil (RSPO) and ISPO certification programs have progressed slowly. Wibowo et al. (2023) investigate incentives that could accelerate certification uptake, finding that increased Fresh Fruit Bunch (FFB) prices, affordable loans, and simplified selling procedures significantly encourage certification. The study underscores the importance of collaboration between the Indonesian government and RSPO to support smallholders.

Addressing smallholder challenges, Raharja et al. (2020) propose a model based on soft system methodology involving smallholder corporations, independent cooperatives, and the Indonesian oil palm association. This model includes cooperatives, farmer groups, and mills supported by regulatory, financial, and input supplier organizations to strengthen smallholder capabilities.

Yuslaini et al. (2023) explore the effects of palm oil sector investment on socioeconomic development, identifying unstable investment climates and social tensions between local communities and commercial actors. To attract investment, the government has developed licensing and non-licensing services. The study discusses palm oil investment's benefits to communities and the environment, emphasizing socioeconomic, ecological, and sustainability aspects.

From a policy intervention perspective, Rudolf et al. (2020) conducted a randomized controlled trial to evaluate strategies promoting native tree planting in oil palm plantations. Both information provision alone and combined with free seedling distribution were effective. The combined approach led to low-intensity planting on many farms, potentially amplifying biodiversity benefits, especially where seedling access was limited.

Brenneis et al. (2023) compared subsidy versus pricing strategies for native tree seedling distribution in Indonesia, finding that subsidies increased tree planting activity without significant negative selection effects, although supported farmers engaged in fewer follow-up plantings. In Nigeria, insufficient funding for input processes in small-scale oil palm fruit processing limits technology adoption in key operations, resulting in income disparities. Adejuwon et al. (2016) recommend policy measures to enhance funding, improve technology infrastructure, address palm oil physicochemical quality, and promote inclusive participation of low-income groups in economic activities.

Smallholder farmers have driven rapid oil palm expansion in tropical regions, especially Indonesia. However, their land-use decisions remain poorly understood and, without proper legislation, may lead to adverse social and environmental outcomes. Euler et al. (2016) found that independent smallholders mainly drive oil palm growth, influenced by regional and village factors, with government concessions accelerating adoption but limited control over overall land-use patterns. Zhao et al. (2023) modelled oil palm production in Riau, Indonesia, showing that consistent landscape-level production could be maintained if existing plantations were replanted after 25 years at a rate of 4% per year. The study highlights the critical role of multi-stakeholder collaboration in sustaining high palm oil yields over time.

Training and Education Support

The study assessed risk management literacy among Malaysian oil palm smallholders, indicating a reasonably high level of literacy, with a strong preference for saving overspending. This demonstrates that smallholders are aware of the importance of financial preparedness as a tool for managing risks. The findings highlight the critical need for ongoing training and awareness initiatives to help smallholders better prepare for potential dangers and develop sustainable long-term revenue sources (Abdullah et al., 2024).

The technological training needs of small-scale oil palm processors in Osun State, Nigeria, were investigated, revealing that 98.6% use both contemporary and traditional methods, with most storing their oil palm in rubber containers. However, challenges such as water scarcity, insufficient funding, unpredictable product pricing, and lack of government support continue to restrict their production capacity. The study found a strong relationship between age, educational level, experience, and extension service demands, while household size did not significantly influence extension requirements (Adeniyi et al., 2019).

CONCLUSION AND RECOMMENDATION

This study systematically reviewed plantation-level technologies in Malaysia's oil palm sector and examined the factors influencing smallholders' readiness to adopt these innovations. The findings reveal that large plantations utilize advanced technologies such as precision agriculture tools, mechanized systems, and data-driven crop monitoring, which significantly improve productivity. However, smallholders remain marginalized from these advancements due to financial, institutional, and informational barriers.

By categorizing key adoption factors into push (training, subsidies, institutional support) and pull (perceived profitability, ease of use, market incentives), the study provides a structured understanding of what encourages or deters smallholder adoption. However, this SLR is limited to English-language peer-reviewed journal articles indexed in SCOPUS and WOS, which may exclude valuable grey literature or case-specific insights from local agencies. The thematic synthesis is also constrained by the heterogeneity of contexts and methodologies used across reviewed papers.

Future research should focus on empirical field studies to test the feasibility and effectiveness of specific plantation technologies at smallholder level. There is also a need to explore financing models, cooperative mechanisms, and localized training strategies that can help bridge the digital and mechanization divide. Stakeholder-focused policy experiments and pilot programs would offer practical insights into scalable technology transfer models.

DECLARATION OF STATEMENT

The authors affirm that this manuscript is original, has not been published elsewhere, and is not currently under consideration for publication in any other journal. All authors have read and approved the final manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest related to the publication of this paper.

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This research did not require ethics approval, as it did not involve human participants, animal subjects, or identifiable personal data.

DATA AVAILABILITY STATEMENT

This study is based on previously published literature that is publicly available through academic databases.

ADDITIONAL INFORMATION

All identifying information related to the authors, their institutions, funders, and approval committees has been provided in the appropriate sections above

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