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Review Article

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Mushroom production in Malaysia: Challenges, sustainable solutions, and future perspectives

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Abstract: Mushroom cultivation has emerged globally as a sustainable agricultural practice due to its ability to convert lignocellulosic waste into high-value food while requiring minimal land use. In Malaysia, despite favorable climatic conditions and abundant agro-industrial biomass, the mushroom industry remains underdeveloped and structurally constrained. This review synthesizes current evidence to examine the major challenges limiting the scalability and sustainability of mushroom production in Malaysia, and to propose integrated, system-based solutions. Key challenges include inconsistent mushroom spawn quality and supply, overdependence on rubberwood sawdust as the primary cultivation substrate, persistent contamination risks, limited environmental control, inefficient post-harvest management, underutilization of spent mushroom substrate (SMS), and fragmented supply chains. These challenges are further exacerbated by low technological adoption, limited technical capacity, and weak institutional support. The analysis highlights that these constraints are not isolated but interconnected across biological, environmental, economic, and institutional dimensions, necessitating holistic interventions rather than fragmented solutions. Sustainable transformation pathways include the development of standardized spawn production and preservation systems, strengthening of reliable spawn supply networks, substrate diversification using agro-residues, adoption of climate-smart cultivation technologies, development of circular economy models for SMS valorization, and improvements in post-harvest management. In addition, inclusive technological innovation, capacity building, and cooperative-based market systems are essential to enhance productivity and resilience, particularly among smallholder producers. Future research should focus on multi-criteria optimization of production systems by integrating economic, environmental, and technical performance, alongside scalable and context-specific innovations. Ultimately, achieving sustainability in Malaysia's mushroom industry requires coordinated efforts across research, policy, and industry to bridge the gap between innovation and field-level adoption.

Keywords: agro-residues, circular economy, climate-smart agriculture, Malaysia, mushroom cultivation, post-harvest losses

1. Introduction

Edible mushrooms have gained increasing global importance as both a food source and a functional ingredient due to their high nutritional value and health-promoting properties. They

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are rich in proteins, dietary fiber, vitamins, minerals, and bioactive compounds such as β-glucans, which have been associated with immunomodulatory and antioxidant effects (Sánchez, 2010; Kalač, 2013). Mushroom cultivation is widely recognition as a sustainable agricultural practice due to its efficiency in converting agricultural waste into edible biomass, its low land requirement, and its role in supporting a circular bioeconomy (Grimm & Wösten, 2018). Unlike conventional crops, mushrooms do not require arable land and can be cultivated on lignocellulosic residues, making them an efficient component of sustainable food systems (Philippoussis, 2009). This ability to convert agricultural waste into high-value food products positions mushroom cultivation as a key strategy for improving food security and environmental sustainability.

To date, at least 350 fungal species have been identified as edible, spanning 18 distinct taxonomic orders (Prescott et al., 2018). This diversity underscores the significant biological and commercial potential of mushroom as a food resource. The global mushroom industry is a rapidly expanding sector, with significant economic value exceeding 42 million tonnes per year. Notably, Asia dominates this output, accounting for the majority of global production (Royse et al., 2017). In Malaysia, commonly cultivated species such as *Pleurotus pulmonarius*, *Ganoderma lucidum*, and *Auricularia* species contribute to food security, rural livelihoods, and agro-industrial development (MARDI, 2020; DOA, 2021). However, the industry remains largely small-scale and reliant on traditional practices, resulting in inefficiencies and vulnerability to resource constraints, and environmental and economic fluctuations.

Recent attention has focused on integrating mushroom cultivation within circular economy frameworks, particularly through the use of agro-industrial residues. Malaysia produces large amounts of lignocellulosic biomass, especially from the oil palm sector, which could serve as alternative substrates for mushroom industry (Yusoff, 2006; Aubrey et al., 2022; Azman et al., 2023). Despite this potential, adoption remains limited due to technical, economic, and institutional barriers.

Overall, the industry is constrained by interconnected challenges related to substrate availability, contamination risks, environmental control, and market structure, limiting its scalability and sustainability (Chang & Wasser, 2017; Grimm & Wösten, 2018). This review evaluates these challenges or constraints faced in mushroom production in Malaysia, and proposes integrated solutions to enhance system resilience, resource efficiency, and circular bioeconomy.

2. Overview of Mushroom Production in Malaysia

Mushroom production in Malaysia is dominated by oyster mushrooms (*Pleurotus* species), particularly grey oyster mushroom (*Pleurotus pulmonarius*), due to their adaptability, rapid growth, strong market demand, and relatively low production costs (Sánchez, 2010; Haimid et al., 2013; Amin et al., 2014; Royse et al., 2017). These advantages make them the most widely cultivated species, especially among smallholder producers. Production data indicate a highly concentrated production system with limited species diversification (Table 1), reinforcing the central role of oyster mushrooms in Malaysia's mushroom industry.

Production trends over recent years show fluctuations in cultivated area and production. The Malaysian mushroom industry over the past five years (2020–2024) exhibits a volatile but overall upward trend, peaking in 2023 before contracting in 2024 (Figure 1). Conventional cultivation systems are primarily based on bagged substrates (commonly referred to as "baglog" systems), composed of rubberwood sawdust as the primary substrate and frequently supplemented with nutrients rice bran and calcium carbonate. The substrates are sterilized, inoculated with spawn, and incubated in semi-controlled environments such as rain-sheltered houses that depend primarily on natural ventilation and ambient humidity (Grimm & Wösten, 2018; Azman et al., 2023). While cost-effective, these constraints increase the sector's

vulnerability to raw material shortages and market price fluctuation, as well as inconsistent yields, due to environmental variability and contamination risks (Chang & Wasser, 2017; Royse et al., 2017).

Table 1. Major mushroom species cultivated in Malaysia.

Mushroom species	Planting percentage
Grey oyster (*Pleurotus pulmonarius*)	90.90%
Ling Zhi (*Ganoderma lucidum*)	1.64%
King oyster (*Pleurotus eryngii*)	1.17%
Black Jelly (*Auricularia* species)	1.17%
Enoki/ Golden needle (*Flammulina velutipes*)	0.70%
White oyster (*Pleurotus florida*)	0.70%
Button mushroom (*Agaricus* species)	0.70%
Shiitake (*Lentinus endodes*)	0.70%
Paddy straw (*Volvariella volvaceae*)	0.47%
Abalon (*Pleurotus cystidiosus*)	0.23%
Other	1.62%

Source: DOA (2015)

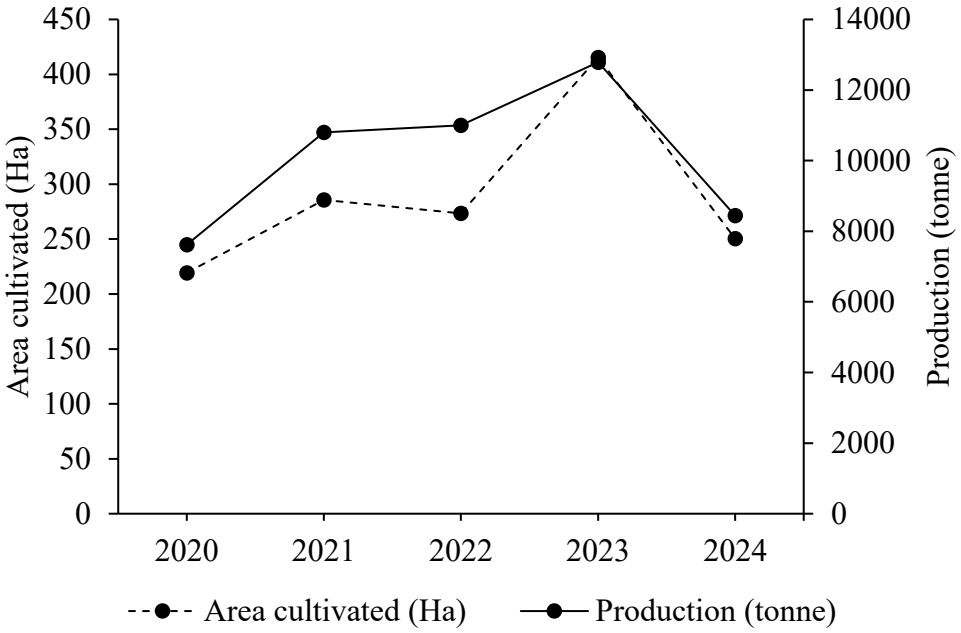

Figure 1. Area cultivated and production of mushroom in Malaysia over the period of five years, 2020 – 2024 (DOA, 2024).

3. Constraints and Solutions

Malaysian mushroom industry is largely composed of small- to medium-scale enterprises, with limited participation from large industrial players (MARDI, 2020; DOA, 2021). This structure reflects both the low entry barrier of mushroom cultivation and the constraints associated with scaling up, including capital requirements, technical expertise, and infrastructure limitations. Most farms rely heavily on semi-manual operations, from substrate preparation to harvesting with limited mechanization and technological integration, which restricts productivity, standardization, and overall operational efficiency.

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Table 2. Key constraints and sustainable solutions in mushroom production in Malaysia.

Aspect	Key constraints	Proposed solutions
Mushroom spawn production, preservation, and supply	Variability in spawn quality and mycelial vigor; risk of contamination during production; deterioration during storage and transportation; need for greater supply reliability and quality standardization.	Optimize solid and liquid spawn production technologies; develop species-specific preservation protocols; establish batch quality testing and traceability; evaluate regional spawn distribution hubs; strengthen research–industry collaboration.
Cultivation substrate	Overdependence on rubberwood sawdust. unstable supply and rising costs; limited adoption of alternative substrates due to technical complexity.	Diversify substrates using agro-residues (oil palm waste, rice straw, bagasse); develop standardized substrate formulations; adopt cost-effective pretreatment (biological, alkaline, steam); strengthen training and extension services.
Contamination and disease management	Contamination by *Trichoderma*, *Aspergillus*, and other microorganisms; inadequate sanitation; contaminated inputs; insufficient biosecurity procedures.	Improve sanitation and facility design; standardize substrate treatment; introduce routine contamination monitoring; strengthen hygiene practices, disease diagnosis, and technical training.
Environmental and climate control	Fluctuating temperature, humidity, CO_2; reliance on semi-controlled systems; high cost of advanced technologies; climate change risks.	Adopt low-cost climate-smart solutions (passive ventilation, evaporative cooling); use IoT monitoring systems; integrate solar-powered systems; promote scalable controlled-environment agriculture.
Post-harvest and marketing	Short shelf life (1–3 days); post-harvest diseases, weak cold-chain; poor packaging; reliance on intermediaries; high losses.	Develop decentralized cold-chain systems; adopt modified atmosphere packaging; promote value-added products (drying, powders); strengthen direct marketing and logistics systems.
Waste management	Disposal via dumping/burning; underutilization of spent mushroom substrate (SMS); economic/logistical barriers.	Valorize SMS into compost, biofertilizer, bioenergy; develop decentralized processing; integrate with agro-industrial systems (e.g., oil palm); create markets and certification for SMS products.
Market and socioeconomic factors	Low consumer awareness; competition from imports; price volatility; limited financing; weak branding and standards.	Improve product diversification and branding; enhance access to finance; develop quality grading systems; strengthen policy and institutional support.
Supply chain limitations	Fragmented, intermediary-driven system; weak logistics and cold chain; low bargaining power of farmers.	Promote cooperative/cluster models; invest in cold-chain infrastructure; adopt digital platforms for marketing and traceability; support value addition.
Technology adoption gap	High cost and complexity of IoT/automation; low digital literacy; uneven adoption.	Develop affordable, user-friendly technologies; provide training and extension; establish demonstration farms; encourage public–private partnerships.
Skills and entrepreneurship	Lack of technical knowledge and standardized practices; weak business and marketing skills.	Implement integrated training (technical + entrepreneurial); strengthen extension services; promote value-added enterprises; develop certification and capacity-building programs.

Malaysia's oil palm industry, however, generates substantial quantities of lignocellulosic biomass such as empty fruit bunches (EFB), palm pressed fiber, and palm kernel shells (Aljuboori, 2013). These agro-residues present significant opportunities for substrate diversification and circular bioeconomy integration. Despite their potential, large-scale adoption remains limited due to technical challenges including substrate pretreatment requirements, inconsistent physicochemical properties, and higher susceptibility to contamination (Aubrey et al., 2022; Azman et al., 2023). Addressing these issues is essential for enhancing resource efficiency, reducing dependency on conventional substrates, and improving the long-term sustainability and resilience of mushroom production systems in Malaysia.

Table 2 summarizes key constraints and corresponding sustainable solutions across the value chain. Major constraints include substrate dependence, contamination, environmental instability, post-harvest inefficiencies, waste management limitation, and weak market systems. The proposed interventions emphasize resource diversification, system standardization, climate-smart and low-cost technologies, value addition, circular waste utilization, and institutional strengthening, highlighting an integrated approach to enhance productivity, resilience, and sustainability in the sector. These aspects were reviewed in the following sections.

3.1 Mushroom spawn: production, preservation, and supply systems

3.1.1 Development and production technologies of mushroom spawn

Mushroom spawn represents a fundamental biological input in mushroom cultivation, directly influencing mycelial establishment, substrate colonization, contamination susceptibility, and subsequent yield performance. The successful development of reliable spawn production systems is therefore essential for improving productivity and consistency in Malaysia's mushroom industry. Spawn production generally involves the establishment and maintenance of pure fungal cultures, followed by the multiplication of mycelium on suitable carrier materials under controlled, aseptic conditions. Common technologies include grain-based and sawdust-based spawn production, while liquid inoculum systems offer opportunities for more standardized and mechanized propagation. The selection of an appropriate technology depends on the cultivated species, inoculum performance, production scale, infrastructure, and economic feasibility (Dong et al., 2026).

Recent advances in spawn production have emphasized improved strain selection, optimized carrier materials, standardized inoculation procedures, and liquid-culture technologies. In Malaysia, the Malaysian Agricultural Research and Development Institute (MARDI) has reported the development of grey oyster mushroom isolates MP 9 and MP 28, solid spawn production using wheat grains, and liquid inoculum production using bioreactor technology. An adjustable-volume liquid spawn injector has also been developed to facilitate inoculation into sawdust-based cultivation bags (MARDI, n.d.). These developments demonstrate opportunities for strengthening domestic spawn production technology. Nevertheless, further evaluation under commercial farm conditions is required to establish their comparative performance, contamination control, cost-effectiveness, and accessibility to small-scale producers.

3.1.2 Preservation of spawn quality and performance

Maintaining spawn quality during storage and handling is equally important because mushroom spawn contains living fungal mycelium whose viability and physiological activity may change over time. Inappropriate storage conditions, prolonged storage periods, microbial contamination, and repeated subculturing of stock cultures may compromise spawn performance, resulting in delayed substrate colonization and inconsistent mushroom yields.

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Therefore, spawn quality management should extend beyond initial production to include the preservation of genetic identity, culture purity, mycelial vigor, and subsequent fruiting capacity.

Strategies for maintaining spawn performance include the use of authenticated stock cultures, standardized propagation procedures, species-appropriate storage conditions, suitable packaging, and routine quality assessments. For long-term preservation of fungal stock cultures, approaches such as cryopreservation may be considered, although their suitability depends on the species and preservation protocol (Kaur et al., 2011). Commercial spawn, in contrast, requires practical storage and distribution procedures that maintain viability until inoculation. Important quality indicators include culture purity, contamination incidence, mycelial regrowth after storage, colonization rate, and biological efficiency. In addition to conventional quality assessment methods, machine learning-based approaches have been investigated for mushroom spawn quality classification (Tongcham et al., 2020). Such approaches may provide opportunities to support more standardized and objective spawn quality assessment, although their practical applicability and cost-effectiveness require further evaluation under Malaysian production conditions. Future Malaysian research should evaluate the storability of locally cultivated mushroom strains under different storage and transportation conditions to establish evidence-based handling recommendations.

3.1.3 Spawn supply and distribution systems in Malaysia

Beyond technological development, a reliable spawn supply and distribution system is essential for ensuring consistent mushroom production. Earlier research on Malaysia's mushroom industry identified poor spawn quality as a production challenge and emphasized the need for a continuous supply of affordable, high-quality spawn (Rosmiza et al., 2016). These findings indicate the importance of considering spawn production not only as a laboratory or farm-level activity but also as a component of the wider agricultural input supply system.

Strengthening spawn distribution in Malaysia requires further assessment of existing suppliers, production capacity, strain availability, quality assurance procedures, geographical accessibility, and transportation practices. Greater attention should be given to standardized batch identification, traceability, storage recommendations, and testing of spawn performance before distribution. Regional spawn production and distribution hubs, supported by collaboration among research institutions, public agencies, private producers, and farmer cooperatives, may offer a practical approach to improving access for smallholder growers. However, the feasibility of these systems should be evaluated through economic and logistical studies rather than assumed.

In the longer term, establishing transparent quality assurance frameworks, strengthening technical training, and improving the commercialization of locally developed spawn technologies could reduce production variability and support a more resilient mushroom industry. Integrating spawn development, preservation, and distribution within Malaysia's broader mushroom production strategy would help ensure that improvements in substrate formulation, environmental control, and disease management translate into consistent productivity gains.

3.2 Cultivation substrate

A central constraint shaping the trajectory of Malaysia’s mushroom industry is its overdependence on rubberwood sawdust as the primary cultivation substrate. While historically advantageous due to its availability and favorable physicochemical properties, this reliance has become increasingly untenable. Structural shifts in the agricultural sector—particularly the long-term decline of the rubber industry and the transition of farmers toward more profitable and less labour-intensive oil palm cultivation (Ali et al., 2021) have reduced the availability of rubberwood resources. This is further compounded by competing demand from higher-value

industries such as furniture manufacturing, which has introduced volatility in both supply and pricing (Akter et al., 2022). This single-resource dependency represents not merely a supply-chain issue, but a systemic bottleneck that amplifies vulnerability across the entire production ecosystem.

From a biological and technical standpoint, substrate quality remains a critical determinant of cultivation success, directly influencing mycelial colonization rates, yield efficiency, and contamination susceptibility (Bellettini et al., 2019). Although a wide range of alternative lignocellulosic residues, such as oil palm biomass, rice straw, and sugarcane bagasse have demonstrated strong potential as viable substitutes, their integration into mainstream production systems remains limited (Aubrey et al., 2022; Devi et al., 2026). This gap reflects persistent technical challenges, including high lignin recalcitrance, suboptimal nutrient composition, specialized machinery, and increased contamination risks. Moreover, the need for pretreatment interventions such as alkaline soaking, steam sterilization, or composting introduces additional layers of operational complexity and cost, thereby discouraging adoption among small- and medium-scale producers. These constraints underscore a broader institutional deficit in substrate standardization, technical training, and effective knowledge dissemination.

Addressing these intertwined challenges requires a systemic transition toward diversified and optimized substrate strategies. Reducing dependence on rubberwood sawdust is not simply a matter of substitution, but of reconfiguring the resource base to enhance resilience and sustainability. The valorization of abundant agricultural residues, particularly from Malaysia's oil palm sector presents a compelling opportunity to align mushroom cultivation with circular economy principles, transforming waste streams into productive inputs (Marlina et al., 2015; Kumla et al., 2020). However, realizing this potential necessitates targeted innovation in substrate formulation and processing.

In this context, the development of standardized substrate blends tailored to specific mushroom species is essential to ensure consistency in performance and reduce production risks (Bellettini et al., 2019). Concurrently, advances in pretreatment technologies must prioritize both efficacy and scalability. While conventional methods such as alkaline treatment and steam sterilization remain effective, their energy and cost implications limit broader applicability. Emerging biological pretreatment approaches, particularly those leveraging ligninolytic microorganisms offer a promising low-energy alternative capable of selectively degrading lignin while preserving cellulose and hemicellulose fractions (Zhang et al., 2002), further supporting the efficient utilization of agro-industrial residues (Kumla et al., 2020). Such approaches not only improve substrate digestibility but also reduce environmental impact, reinforcing the sustainability profile of mushroom production systems.

Crucially, the success of these technological innovations hinges on the strength of institutional support mechanisms. Bridging the gap between research and practice requires robust extension services, farmer training programs, and accessible demonstration models that facilitate knowledge transfer and reduce adoption barriers. Without such institutional capacity building, even the most promising technical solutions risk remaining confined to experimental settings.

3.3 Contamination and disease management

Contamination and disease represent persistent biological challenges in mushroom cultivation, affecting productivity, crop quality, and economic returns. Among the most problematic contaminants are *Trichoderma* species (green mould), which exhibit rapid mycelial growth and strong competitive interactions that can suppress the development of cultivated mushroom mycelia (Altaf et al., 2022). Other filamentous fungi, including *Aspergillus*, *Penicillium*, and *Neurospora* species, are also associated with contamination of cultivation substrates and production environments. These microorganisms may compete with cultivated mushrooms for

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nutrients and space, disrupt substrate colonization, and contribute to production losses, particularly under conditions favorable to their proliferation (Miles & Chang, 2004; Pitt & Hocking, 2009). In Malaysia, the warm and humid tropical environment creates additional challenges for managing microbial contamination, particularly in small-scale cultivation facilities where environmental regulation and sanitation practices may be limited.

Contamination risks extend beyond the cultivation substrate and may arise at multiple stages of mushroom production, including substrate preparation, inoculation, incubation, and fruiting. Airborne fungal spores, contaminated water, inadequately sanitized equipment, and personnel movement can facilitate the introduction and spread of unwanted microorganisms within cultivation facilities (Kim et al., 2019; Ajis et al., 2024; Xiong et al., 2025). Furthermore, inadequate substrate treatment, improper handling practices, and insufficient separation between clean and contaminated production areas may increase the likelihood of contamination. These interconnected pathways indicate that contamination should be managed as a system-wide biological risk rather than as an isolated problem associated with substrate sterilization.

Effective contamination and disease management therefore requires a preventive and integrated biosecurity approach throughout the cultivation cycle. At the substrate preparation stage, appropriate sterilization or pasteurization procedures, depending on the mushroom species and production system, are essential for reducing competing microorganisms. During inoculation and incubation, hygienic handling, sanitized equipment, suitable airflow management, and spatial separation of critical production stages can help minimize contamination risks. Routine sanitation, management of water quality, proper disposal of contaminated cultivation bags, and regular monitoring of production environments should be incorporated into standardized operating procedures. These measures are particularly important for smallholder production systems, where low-cost preventive practices may offer more practical opportunities for reducing crop losses than highly capital-intensive technologies.

The effectiveness of biosecurity measures is also influenced by the biological quality of cultivation inputs, particularly mushroom spawn. High-quality spawn with vigorous mycelial growth can promote rapid and uniform substrate colonization, potentially reducing opportunities for competing microorganisms to establish. Conversely, contaminated or physiologically weakened spawn may introduce biological risks at the beginning of the cultivation cycle. Therefore, preventive contamination management should be closely coordinated with standardized spawn production, preservation, and quality assurance practices, as discussed in Section 3.1. Nevertheless, the use of high-quality spawn alone cannot eliminate contamination risks arising from inadequate substrate treatment, poor hygiene, or unfavorable cultivation conditions.

Beyond conventional sanitation practices, improved disease surveillance and early contamination detection offer opportunities to strengthen biosecurity management. Regular inspection of cultivation bags, documentation of contamination symptoms, and monitoring of contamination incidence can support the identification of recurring problems and facilitate timely corrective actions. Where necessary, laboratory-based identification of suspected contaminants can improve diagnostic accuracy and inform appropriate management strategies. The integration of affordable environmental sensors and digital recordkeeping systems may further support the monitoring of production conditions and contamination patterns, although their practical effectiveness and economic feasibility require evaluation under different Malaysian cultivation systems.

Ultimately, sustainable contamination and disease management in Malaysia's mushroom industry depends on integrating preventive biosecurity, standardized cultivation practices, reliable diagnostic support, and technical capacity building. Future research should prioritize the identification of dominant contaminants under local production conditions, evaluation of

contamination pathways, and development of cost-effective disease prevention strategies suited to different cultivation scales. Strengthening extension services, farmer training, and institutional collaboration would facilitate the adoption of these practices, particularly among smallholder producers. A coordinated approach emphasizing prevention, early detection, and continuous improvement of cultivation hygiene is essential for reducing biological losses and enhancing the productivity, resilience, and sustainability of Malaysia's mushroom industry.

3.4 Environmental and climate control

Environmental variability significantly affects mushroom production. While the tropical climate provides inherently favorable conditions in ambient temperature and humidity, these advantages are offset by pronounced fluctuations in microclimatic parameters. Variability in temperature, relative humidity, and CO_2 concentration has been shown to directly affect physiological processes, resulting in inconsistent yields, morphological defects, and reduced product quality (Sánchez, 2010). Mahmud et al. (2018) and Khalib et al. (2024) demonstrated that poor regulation of key environmental variables, including temperature, humidity, substrate moisture, and CO_2 concentration, contributes directly to cultivation failure and unstable mushroom development, particularly in small-scale oyster mushroom production systems. These challenges are especially acute in production systems that lack precise environmental control.

In practice, a substantial proportion of Malaysian mushroom farms operate under semi-controlled conditions, relying on manual ventilation, rudimentary watering systems, and passive shading. Such approaches provide only limited capacity to stabilize critical growth parameters, leaving production systems highly sensitive to external climatic variability. Controlled-environment agriculture (CEA) research has consistently demonstrated that tight regulation of temperature, humidity, and gas exchange is essential for optimizing yield performance and ensuring uniform crop quality (Balogo & Wenceslao, 2025). However, the transition toward fully controlled systems remains constrained by significant economic and technical barriers. High capital investment, elevated energy consumption, and limited technical expertise, particularly among smallholder producers, restrict the scalability of advanced environmental control technologies. In addition, manual monitoring practices remain labor-intensive and often fail to provide continuous real-time assessment of environmental fluctuations, resulting in delayed corrective actions and increased production inefficiencies.

Addressing these constraints requires a strategic shift toward climate-smart and resource-efficient environmental management systems. CEA offers clear benefits in terms of precision and control, but its adoption in the Malaysian context depends on the development of cost-effective and scalable alternatives. In this regard, low-energy innovations such as passive ventilation designs, evaporative cooling systems, and improved insulation techniques provide practical entry points for enhancing environmental regulation without imposing prohibitive costs. These approaches can significantly moderate temperature and humidity fluctuations, thereby stabilizing growth conditions while maintaining economic feasibility.

Complementing these physical interventions, the integration of affordable, IoT-based monitoring systems represents a transformative opportunity for data-driven cultivation. Real-time tracking of environmental parameters enables producers to make informed management decisions, optimize resource use, and respond proactively to emerging stresses. Importantly, such technologies can be adapted to varying scales of production, making them accessible to smallholders while still delivering measurable improvements in efficiency and consistency (Madzhi et al., 2025; Villafuerte et al., 2025). For example, Mahmud et al. (2018) developed an IoT-based environmental monitoring system for mushroom cultivation integrating DHT11 temperature–humidity sensors, MQ135 CO_2 sensors, ESP8266 Wi-Fi modules, and the ThingSpeak cloud platform for real-time monitoring and automated irrigation control. Field

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validation in mushroom houses in Johor, Malaysia, demonstrated sensor performance comparable to a commercial HT-2000 data logger, highlighting the reliability of low-cost sensor networks for practical farm management. Similarly, Khalib et al. (2024) emphasized the importance of integrated environmental monitoring in small-scale oyster mushroom cultivation to minimize crop failure associated with fluctuations in temperature, humidity, substrate moisture, and CO_2 concentration. Collectively, these studies demonstrate that affordable IoT-assisted cultivation systems can enhance environmental regulation, improve production consistency, and reduce labor dependency among smallholder mushroom producers.

Solar-powered environmental control systems further extend the sustainability potential of these innovations by reducing dependence on grid electricity and lowering operational costs. This is particularly relevant in rural or off-grid contexts, where energy access may be limited or unreliable. By coupling renewable energy solutions with adaptive environmental control strategies, producers can enhance both economic viability and ecological sustainability (Konain et al., 2023).

Recent advances in artificial intelligence (AI), machine learning, and integrated environmental management systems improve the efficiency of mushroom cultivation by simultaneously optimizing temperature, humidity, ventilation, lighting, and substrate moisture (Irwanto et al., 2024). These technologies enable real-time monitoring and predictive analysis to identify stress conditions early, enhance resource efficiency, reduce energy and operational costs, and support stable production performance through precision agriculture practices (Villegas-Ch et al., 2024).

3.5 Post-harvest and marketing

Mushroom are highly perishable, with a short shelf life due to their high moisture content and elevated respiration rates that leads to significant losses (Wakchaure, 2011). Post-harvest management constitutes a critical yet often under-optimized segment of Malaysia's mushroom value chain, where biological fragility intersects with infrastructural and market limitations. This narrow post-harvest window creates acute logistical pressures and contributes to substantial quantitative and qualitative losses. Consequently, inefficiencies beyond the farm gate, rather than production constraints alone, emerge as a major determinant of overall sector performance and profitability.

A range of structural challenges underpins these losses. Limited access to cold-chain infrastructure restricts the ability to maintain optimal storage temperatures during handling, transportation, and retail. In parallel, inadequate packaging systems do not effectively regulate gas exchange and moisture retention, accelerating physiological deterioration. These technical deficiencies are compounded by market-related constraints, including heavy reliance on intermediaries and limited access to high-value or differentiated markets. The result is a fragmented value chain in which producers capture only a small share of final market value, while bearing disproportionate risks associated with spoilage and price volatility.

Although technologies such as refrigeration and modified atmosphere packaging (MAP) have demonstrated clear efficacy in extending shelf life and preserving product quality (Jafri et al., 2013), their adoption remains uneven. High capital costs, limited infrastructure, and insufficient technical knowledge, particularly among small-scale producers, act as significant barriers. This disconnect highlights a broader systemic issue, where post-harvest innovation has not been sufficiently integrated into mainstream production systems, despite its central importance to value chain efficiency.

Addressing these challenges requires a paradigm shift toward integrated post-harvest management and value chain optimization. Investment in scalable cold-chain solutions represents a foundational priority. Rather than relying solely on large, centralized refrigeration systems, decentralized and modular cold storage, potentially powered by renewable energy,

offers a more accessible pathway for smallholders. Such systems can significantly reduce spoilage rates while enhancing flexibility in distribution and marketing.

Concurrently, advances in packaging innovation must be leveraged to improve product preservation. Modified atmosphere packaging, along with emerging biodegradable and moisture-regulating materials, can extend shelf life without imposing excessive environmental burdens. Standardizing packaging protocols tailored to specific mushroom species and market requirements would further enhance consistency and reduce post-harvest variability (Jafri et al., 2013; Castellanos-Reyes et al., 2021).

Beyond technical interventions, strengthening value chain integration is essential for improving economic outcomes. The development of value-added products, such as dried mushrooms, powders, and nutraceutical formulations, provides a strategic avenue for reducing dependence on highly perishable fresh markets. These products not only extend shelf life but also open access to new market segments, including health and functional food industries, thereby increasing revenue diversification.

Equally important is the reconfiguration of market linkages. Expanding direct marketing channels, including digital platforms and farm-to-consumer models, can enhance price transparency and reduce reliance on intermediaries. By shortening the supply chain, producers are better positioned to capture value while responding more dynamically to market demand. Logistics optimization through improved coordination, aggregation, and distribution systems, further complements these efforts by enhancing efficiency and reducing time-to-market (Singh et al., 2010; Walia et al., 2025).

3.6 Waste management and circular economy

Spent mushroom substrate (SMS) represents a critical intersection between waste management and resource efficiency in Malaysia's mushroom industry. Notably, for every kilogram of mushrooms produced, approximately five kilograms of SMS are generated—a ratio consistently reported across the literature and indicative of the considerable biomass accumulation associated with mushroom production systems (Lin et al., 2014; Grimm & Wösten, 2018; Grdović et al., 2023). Therefore, based on Malaysia's fresh mushroom production in 2024, it is estimated that approximately 42,226 tonnes of SMS were generated. The material is rich in organic matter, residual nutrients, and partially degraded lignocellulosic material (Mortada et al., 2020; Sabaratnam et al., 2024). Despite this intrinsic value, prevailing management practices remain largely unsustainable, with open dumping and burning still widely observed. These approaches not only contribute to environmental degradation through greenhouse gas emissions and nutrient loss, but also reflect a systemic inefficiency in resource utilization (Zhang et al., 2020).

This underutilization is particularly striking given the well-documented potential of SMS as a secondary resource. A growing body of research demonstrates that SMS can be effectively repurposed into compost, biofertilizers, and bioenergy feedstocks, thereby contributing to circular economy models and enhancing overall system sustainability (Zhang et al., 2002; Grimm & Wösten, 2018). However, the transition from disposal to valorization is not straightforward. Economic and logistical constraints, including high transportation costs, the need for processing infrastructure, and uncertain market demand create a persistent trade-off that often favors low-cost disposal over resource recovery. These barriers are especially pronounced for small- and medium-scale producers, who may lack both the capital and the market access required to operationalize SMS reuse strategies.

Addressing this challenge requires a systemic reconfiguration of how SMS is perceived and managed within the production landscape. Rather than treating SMS as a residual waste stream, it must be repositioned as a co-product within an integrated bioresource system. Central to this transition is the development of decentralized processing models that reduce

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transportation burdens and enable on-site or near-site valorization. Technologies such as small-scale composting units, anaerobic digestion systems, and substrate recycling processes can be adapted to local conditions, improving economic feasibility while minimizing environmental impact (Martín et al., 2023). Nevertheless, the broader adoption of SMS-derived products is strongly influenced by the level of public awareness and farmer acceptance. A significant number of farmers still possess limited understanding of the agronomic advantages, suitable usage practices, and long-term economic benefits associated with SMS-based materials, which consequently hinders their widespread adoption despite their demonstrated effectiveness.

Equally important is the creation of localized markets for SMS-derived products. Establishing demand for compost, organic fertilizers, and biomass-based energy inputs can significantly enhance the economic viability of valorization pathways. This requires coordinated efforts to standardize product quality, develop certification frameworks, and promote awareness among end-users, particularly within the agricultural sector. In this context, SMS-derived inputs can play a strategic role in reducing dependence on synthetic fertilizers, thereby contributing to broader sustainability goals (Martín et al., 2023).

A particularly promising avenue for sustainable intensification lies in the integration of mushroom cultivation with existing agro-industrial systems, especially Malaysia's oil palm sector. From a circular economy perspective, this integration enables closed-loop biomass utilization, whereby agricultural residues such as oil palm biomass are repurposed as substrates for mushroom production, while the resulting spent mushroom substrate (SMS) is subsequently recycled into compost, soil amendments, livestock feed supplements, or bioenergy feedstocks. This cascading utilization model reflects principles of industrial symbiosis, in which waste streams from one agricultural subsystem become productive inputs for another, thereby enhancing resource efficiency, reducing environmental externalities, and supporting sustainable biomass management in line with national sustainability priorities (Martín et al., 2023).

Ultimately, the effective valorization of spent mushroom substrate (SMS) depends on the integration of technological innovation, economic incentives, and institutional support. Policies promoting waste-to-resource transitions through subsidies, technical assistance, low-interest financing, and public–private partnerships can help overcome adoption barriers, particularly among small- and medium-scale producers. Equally important is the strengthening of extension services and knowledge transfer mechanisms to facilitate the translation of research into scalable industrial applications. Collaboration among government agencies, researchers, industry stakeholders, and farming communities will be critical for accelerating technology transfer, market development, and the wider adoption of sustainable SMS management practices.

3.7 Market, policy, and socioeconomic

The development trajectory of Malaysia's mushroom industry is shaped not only by technical production constraints but also by broader market, policy, and socioeconomic conditions. Structural limitations in financing, institutional coordination, market organization, and technological accessibility collectively influence the sector's capacity for sustainable growth. These interrelated constraints highlight the importance of adopting a systems-based policy framework that simultaneously addresses production efficiency, market integration, social inclusion, and innovation diffusion.

In addition to technical challenges, structural and socioeconomic factors significantly constrain the development of the Malaysian mushroom industry. Market-related issues include low consumer awareness of diverse mushroom products, competition from imported mushrooms, price volatility, and limited value-added processing. Smallholder producers also face barriers such as limited access to capital, inadequate technical training, and fragmented supply chains. The lack of standardized quality grading and branding further restricts access to

high-value markets. Moreover, the adoption of modern technologies such as IoT-based environmental monitoring and automated climate control remains uneven. While these technologies have demonstrated strong potential to improve productivity and efficiency, their high initial cost and technical complexity limit accessibility among small-scale producers (Wolfert et al., 2017). This digital divide contributes to disparities in innovation capacity and production performance across the sector. Collectively, these interconnected challenges highlight the need for integrated, system-level interventions that address technical, economic, and institutional constraints simultaneously.

3.7.1 Supply chain

The mushroom supply chain in Malaysia typically involves multiple intermediaries, progressing from producers to collectors, wholesalers, retailers, and finally consumers. Within this fragmented structure, value addition and pricing power are often concentrated downstream, while producers retain limited influence over market pricing and distribution decisions. Inadequate coordination among supply chain actors contributes to inefficiencies in inventory management, transportation scheduling, quality standardization, and cold-chain maintenance, thereby increasing spoilage risks and reducing overall market efficiency.

Supply chain inefficiencies remain a structural constraint in Malaysia's mushroom industry, where fragmented, intermediary-driven systems reduce price transparency and compress producer margins. Smallholder farmers, in particular, face limited bargaining power within informal and poorly coordinated distribution networks. These challenges are compounded by inadequate transportation infrastructure, weak cold-chain systems, and inefficient logistics, resulting in significant post-harvest losses and quality deterioration, especially in rural areas (Castellanos-Reyes et al., 2021; Silva et al., 2024).

Addressing these constraints requires a transition toward integrated and technology-enabled value chains. Cooperative and cluster-based models offer a practical pathway to improve coordination, aggregate supply, and strengthen collective bargaining. By enabling shared access to infrastructure such as cold storage and transportation, these models reduce transaction costs and enhance market efficiency (Barrett et al., 2012).

Investment in decentralized and energy-efficient cold-chain solutions such as solar-powered refrigeration and insulated packaging is critical for extending shelf life and stabilizing supply under tropical conditions (Jafri et al., 2013; Castellanos-Reyes et al., 2021; Silva et al., 2024). Complementarily, digital platforms (e-commerce, mobile apps) can facilitate direct marketing, improve price discovery, and enhance traceability, thereby reducing reliance on intermediaries and improving supply–demand alignment (Wolfert et al., 2017).

Value addition through processing (e.g., dried mushrooms, powders) further reduces dependence on highly perishable fresh markets while enabling access to higher-value segments (Castellanos-Reyes et al., 2021). Finally, policy support through incentives for cooperative formation, infrastructure investment, and quality standardization remains essential for enabling supply chain modernization. In sum, integrating organizational innovation, logistics infrastructure, digitalization, and policy support is key to building a more efficient, resilient, and inclusive mushroom supply chain (Silva et al., 2024).

3.7.2 Awareness and adoption of new technologies

Technological innovation represents a critical lever for advancing productivity and sustainability in Malaysia's mushroom sector, yet its adoption remains markedly uneven. While advanced tools such as IoT-based environmental monitoring, automated climate control systems, and data-driven farm management platforms have demonstrated substantial benefits in optimizing resource use and improving decision-making (Madzhi et al., 2025; Villafuerte et al., 2025), their deployment is largely confined to a small subset of well-capitalized commercial

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operations. Based on the study by Ruslan et al. (2025), the awareness gap refers to the disconnect where smallholder growers continue to rely on conventional farming methods despite the existence of modern technologies that could solve their productivity issues. This uneven uptake has created a widening technological divide, reinforcing disparities in productivity, resilience, and innovation capacity across the sector.

The persistence of this gap reflects a combination of structural and institutional barriers. High initial investment costs remain a primary constraint, particularly for smallholder producers operating under tight financial margins. In addition, the technical complexity of digital systems, coupled with limited access to training and support services, further inhibits adoption. Low levels of awareness and digital literacy compound these challenges, resulting in continued reliance on conventional, experience-based practices. While such practices may be locally adapted, they often lack the precision and responsiveness required to manage increasingly complex environmental and biological risks (Wolfert et al., 2017).

This technological inertia has broader implications for sectoral development. Farms that are unable to integrate modern monitoring and control systems are more vulnerable to fluctuations in climate, contamination pressures, and input variability. Consequently, the uneven diffusion of innovation not only limits aggregate productivity gains but also undermines the sector's overall resilience and competitiveness.

Addressing these challenges requires a deliberate shift toward inclusive and context-sensitive technological development. Rather than prioritizing high-end, capital-intensive solutions alone, innovation pathways must emphasize affordability, modularity, and ease of use. The development of low-cost IoT-based sensors, simplified automation systems, and mobile-integrated management platforms offers a practical entry point for smallholder adoption. Such technologies should be designed with user-centric interfaces and minimal maintenance requirements to ensure accessibility across varying levels of technical expertise.

Equally critical is the strengthening of human and institutional capacity to support digital transformation. Targeted training programs, extension services, and capacity-building initiatives are essential for enhancing digital literacy and enabling producers to effectively utilize emerging technologies. In this context, knowledge transfer mechanisms must move beyond one-way dissemination toward participatory models that integrate farmer feedback and local adaptation.

Public–private partnerships can play a catalytic role in accelerating technology diffusion. By leveraging the complementary strengths of research institutions, technology providers, and government agencies, such collaborations can facilitate the development, financing, and scaling of appropriate technologies. Demonstration farms and pilot projects, in particular, serve as effective platforms for showcasing tangible benefits, reducing perceived risks, and building trust among producers.

Furthermore, the integration of digital technologies into broader agricultural support systems such as financing schemes, input supply networks, and market platforms can enhance their value proposition and encourage adoption. For example, linking environmental monitoring data to advisory services or predictive analytics can enable more proactive and informed farm management, thereby translating technological capability into measurable productivity gains.

Bridging the technological divide within Malaysia's mushroom industry requires a holistic approach that aligns innovation with inclusivity. Sustainable intensification will depend not only on the availability of advanced technologies but also on the capacity of producers to access, understand, and effectively implement them. By fostering an enabling ecosystem that combines affordable tools, institutional support, and collaborative innovation, the sector can unlock the full potential of digital agriculture while ensuring equitable and resilient development.

Infrastructure limitations remain a major barrier to the adoption of digital technologies among mushroom producers, especially in rural areas with unreliable internet connectivity and electricity supply (Alabdali et al., 2023). Limited digital literacy and resistance to technological change further hinder adoption among smallholders. Therefore, continuous technical support, localized training programs, and user-friendly technologies are essential to improve accessibility, encourage adoption, and support smart farming development.

In conclusion, technological innovation has significant potential to improve productivity, sustainability, and resilience within Malaysia's mushroom industry. However, unequal access to advanced technologies, financial limitations, inadequate infrastructure, and low digital literacy continue to hinder widespread adoption, particularly among smallholder producers (Neumeyer et al., 2021). Addressing these challenges requires inclusive and affordable technological solutions supported by training, institutional collaboration, and strong infrastructure development. By fostering accessible smart farming systems and strengthening human capacity, the mushroom sector can achieve more equitable, efficient, and sustainable growth while enhancing its adaptability to future environmental and economic challenges.

3.7.3 Skills, training, and entrepreneurship gaps

Human capital constraints represent a foundational bottleneck in the evolution of Malaysia's mushroom industry, shaping both production efficiency and the sector's capacity for innovation. A significant proportion of producers continue to rely on informal knowledge systems and experiential learning, resulting in heterogeneous cultivation practices and inconsistent production outcomes. While such tacit knowledge can be adaptive, its lack of standardization often leads to inefficiencies in critical domains, including substrate formulation, contamination management, environmental control, and post-harvest handling. These gaps not only limit biological performance but also exacerbate vulnerability to production risks (Haimid et al., 2013).

Beyond technical competencies, deficiencies in entrepreneurial capacity further constrain sectoral development. Many producers lack formal training in business planning, branding, product diversification, and market engagement, restricting their ability to scale operations or access higher-value markets. As a result, production remains largely oriented toward low-margin fresh markets, with limited integration into value-added or differentiated supply chains. This dual deficit technical and entrepreneurial reflects a broader institutional shortfall in structured training systems, extension services, and coordinated knowledge transfer mechanisms (Rosmiza et al., 2016).

Addressing these challenges requires a systemic investment in human capital development as a core pillar of sustainable intensification. Capacity-building initiatives must be both comprehensive and context-specific, integrating technical training with entrepreneurial skill development. On the technical front, standardized training modules should focus on optimizing substrate formulations, implementing effective contamination control strategies, and managing environmental parameters with precision. Equally important is the incorporation of post-harvest management practices, ensuring that gains achieved during production are not undermined along the value chain (Becerra-Encinales et al., 2024).

In parallel, strengthening entrepreneurial competencies is essential for enabling producers to transition from subsistence-oriented cultivation to market-driven enterprises. Training programs should encompass business model development, financial management, branding strategies, and market analysis, thereby equipping producers with the tools needed to diversify products and capture greater value. The promotion of value-added processing such as dried mushrooms, functional foods, and specialty products can further enhance income stability and reduce reliance on volatile fresh markets (Sangeeta et al., 2024).

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Central to these efforts is the reinforcement of institutional linkages. Effective knowledge transfer depends on strong collaboration between research institutions, government agencies, and industry stakeholders (Rashid et al., 2024). Extension services must be revitalized to serve as active intermediaries, translating scientific advancements into practical applications while facilitating feedback loops from producers (Syahirah et al., 2025). Demonstration farms, training hubs, and digital learning platforms can play a pivotal role in scaling knowledge dissemination and fostering peer-to-peer learning networks.

Policy support is equally critical in creating an enabling environment for human capital development. Targeted interventions, such as training subsidies, access to financing, infrastructure investment, and the establishment of quality standards can incentivize participation and enhance the overall effectiveness of capacity-building programs. In particular, certification systems for production practices and inputs can promote standardization, improve market confidence, and facilitate access to premium market segments.

The long-term sustainability and competitiveness of Malaysia's mushroom industry hinge on its ability to cultivate not only mushrooms, but also skilled and adaptive producers. By embedding human capital development within a broader framework of institutional strengthening and policy support, the sector can enhance productivity, drive innovation, and build resilience in the face of evolving economic and environmental challenges (Luo et al., 2025).

4. Future Research and Conclusion

Sustainable transformation of Malaysia's mushroom industry requires a shift from fragmented, input-driven practices toward integrated, systems-based approaches that address the interdependencies among biological, environmental, economic, and institutional factors. Research priorities include multi-criteria optimization models that extend beyond yield to incorporate economic feasibility, environmental performance, and scalability. Life cycle assessment and techno-economic analysis provide robust frameworks for evaluating trade-offs and resolving the sustainability paradox wherein environmentally favorable solutions may lack economic viability at the farm level.

Future research should prioritize the optimization of mushroom spawn production and preservation technologies suited to Malaysia's tropical conditions. Comparative evaluation of solid and liquid spawn production systems, strain stability, mycelial vigor, contamination incidence, storability, and yield performance would provide evidence for developing standardized spawn quality protocols. In addition, techno-economic assessments of decentralized spawn production facilities and regional distribution networks are needed to identify scalable and affordable solutions, particularly for smallholder mushroom producers.

Technological development should emphasize low-cost, modular systems for environmental control and monitoring suited to smallholder contexts. Solar-powered operations and microbiome-based biosecurity strategies offer promising pathways for reducing costs while shifting contamination management from energy-intensive sterilization toward biologically informed approaches. Value chain integration through digital platforms, cooperative structures, and blockchain-enabled traceability can enhance coordination and market access, though successful implementation requires institutional support and stakeholder collaboration. Circular economy advancement depends on establishing viable spent mushroom substrate valorization models, particularly through integration with the oil palm sector. Human capital development remains foundational, requiring capacity-building models that combine technical training with entrepreneurial skills, alongside strengthened research-extension-industry linkages. Policy research should inform enabling regulatory frameworks and quality standardization systems.

In conclusion, Malaysia's mushroom industry faces a critical juncture where structural challenges coexist with significant growth opportunities. Progress requires transitioning from

incremental improvements toward system-level transformation through substrate diversification, climate-smart technologies, circular economy integration, and digital innovation, all aligned with local socio-economic realities to ensure accessibility for smallholder producers. Coordinated efforts across research, industry, and policy domains can position Malaysia's mushroom sector as a model for sustainable tropical agri-food systems aligned with climate-smart agriculture and circular bioeconomy goals.

Data Availability

No new data were generated for this study. All information discussed in this review is derived from previously published articles, which are cited in the reference list.

Author Contributions

Mohd. Rashid Mohd. Rakib: Conceptualization, Resources, Writing - Original Draft. **Clament Fui Seung Chin:** Writing - Review & Editing. **Ilmas Abdurofi:** Writing - Review & Editing. **Nor Jawahir Abu:** Writing - Original Draft. **Siti Saripa Rabiah Mat Lazim:** Writing - Review and Editing. Sumaiyah Abdullah: Writing - Review and Editing.

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Conflicts of Interest

Mohd. Rashid Mohd. Rakib is the Editor-in-Chief of this journal. To ensure an unbiased review process, the author was recused from all editorial handling, peer review, and decision-making related to this article. The article was managed independently by another editor in accordance with the journal's editorial policies.

Ethics Statement

Ethics approval was not applicable for this review study.

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