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Innovative approaches to enhancing sustainability in the engineered wood processing industry in Malaysia

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ABSTRACT

The growing demand for engineered wood products (EWP) in Malaysia has intensified wood processing activities, raising sustainability and environmental concerns. This study aims to identify innovative strategies to strengthen sustainability practices in the Malaysian EWP industry. A mixed-methods approach was employed, combining a survey of 67 stakeholders, semi-structured interviews with 11 experts and site assessments of five manufacturing companies to capture current practices, barriers and enabling factors. The survey indicates moderate adoption of sustainability practices. A majority of firms practiced waste minimization and use of recyclable wood (65%), adopted energy conservation policies (55%), utilised wood waste for fuel or feedstock (55%) and applied emission control systems (55%). In contrast, adoption of advanced measures was lower, with 35% incorporating solar energy and 15% applying lifecycle assessment (LCA). The analysis revealed four key innovation pathways: (i) resource management and waste reduction, (ii) energy efficiency and emissions reduction, (iii) technological innovation and adoption and (iv) circular economy and sustainable sourcing. Implementation challenges were grouped into four categories: financial, technical, operational and institutional, highlighting limited investment, weak policy support and shortages of skilled professionals. The study emphasizes that strengthening institutional capacity, establishing credible policy anchors, enhancing technical expertise, capacity-building through training and research and stakeholder collaboration are critical to accelerating sustainability adoption. The study highlights key gaps in the adoption of sustainability and innovation in the EWP industry. The findings establish an evidence base to strengthen policies, industry practices and stakeholder collaboration, supporting actionable strategies toward a more sustainable and competitive EWP sector.

Introduction

The wood industry plays a crucial role in Malaysia's economic growth, especially through engineered wood products (EWP), like plywood, particleboard and medium-density fiberboard (MDF). Despite this, the rapid expansion of EWP production has intensified environmental pressures, including deforestation, carbon emissions, fossil fuel dependency and large volumes of wood waste (Samad, 2009; Rosli et al., 2019; Mokhtar et al., 2022). Between 1990 and 2020, Malaysia lost over 14 million hectares of forest, making it one of the fastest deforesting nations in Southeast Asia (Ramasamy, 2015; Purbasari et al., 2020). Notably, the wood processing industry itself consumes a large part of fossil fuels and emits greenhouse gases (Waltersmann et al., 2021). The sector also contributes roughly 10 % of the nation's industrial carbon emissions (Kahar et al., 2021), which emphasizes the need to implement more sustainable practices.

Although initiatives such as the MTCS and FSC certification have encouraged sustainable practices, persistent challenges remain. These include reliance on non-renewable energy, the environmental burden of synthetic adhesives, underutilization of reclaimed materials and slow adoption of cleaner technologies (Loke et al., 2014; Noraida et al., 2017; Ferdosian et al., 2017; Goncalves et al., 2021; Amarasinghe et al., 2024). Besides, some efforts to shift toward cleaner energy and cut harmful emissions have been implemented, but the industry's collective emissions continue to worsen the country's carbon footprint and environmental deterioration (Ramasamy, 2015; Yusof et al., 2018; Jamaludin et al., 2024). The lack of understanding stems from the absence of

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Nomenclature

EWP	Engineered Wood Products
LCA	Life Cycle Assessment
FSC	Forest Stewardship Council
MDF	Medium-Density Fibreboard
MTCC	Malaysian Timber Certification Council
MTCS	Malaysian Timber Certification Scheme
PEFC	Programme for the Endorsement of Forest Certification
VOC	Volatile Organic Compounds
SDGs	Sustainable Development Goals

thorough research that evaluates the impact of such initiatives and assesses key factors for their limited implementation in Malaysia's EWP industry. More critically, the sector has yet to embrace innovative approaches that could transform sustainability outcomes, such as renewable energy integration, advanced LCA and circular economy models.

Existing studies on sustainability in EWP are fragmented, often focusing on specific issues such as deforestation, waste management, or energy use (Turan et al., 2017). However, they rarely adopt an integrated perspective, leaving several gaps. First, the absence of LCA studies limits understanding of the full environmental impacts of EWP from extraction to disposal (Barbhuiya & Das, 2023). Second, the effective implementation of circular economy practices, specifically recycling and residue management, in Malaysia remains largely unknown (Hsiao & Hu, 2024). Third, local contexts continue to under-explore the practicality and effectiveness of certification systems like FSC (Lintangah et al., 2022).

This study responds to these gaps by examining innovative approaches to enhancing sustainability in Malaysia's EWP industry. The main objectives are to investigate current adoption levels of sustainable practices, identifies four key innovation pathways: resource management and waste reduction, energy efficiency and emissions control, technological innovation and adoption and circular economy and sustainable sourcing and highlights the institutional, financial, technical and operational challenges that hinder their implementation. By integrating these perspectives, the study establishes an evidence base to guide policymakers, industry stakeholders and researchers in advancing innovative, practical strategies to support Malaysia's transition towards a more sustainable EWP industry.

This paper is organized as follows: Section 1 and Section 2 include background information on EWP. The methods and data collection are covered in Section 3, while Section 4 delves into results and discussion. The conclusion in Section 5 is centered on the derived strategies coupled with the designed mitigative approaches concerning the EWP in Malaysia.

Background

Overview of previous studies on the sustainability approaches in the EWP industry

The EWP industry has a significant impact on the practices within forestry and construction, as well as its innovative potential for further sustainability. As highlighted in Adhikari and Ozarska (2018), managing resources through reducing waste in conjunction with energy consumption in EWP processes is vital for minimizing the ecological footprint. One important direction of research is the enhancement of production processes for better energy efficiency and lower greenhouse gas emissions. For example, some researchers have investigated how biomass and solar energy can be used in wood processing plants in place of fossil fuels to reduce the carbon footprint (Bras et al., 2025). Other studies note that the introduction of sophisticated manufacturing techniques and other digital technologies is equally crucial in optimizing production processes and reducing carbon footprint (Chen et al., 2023). Moreover, principles of the circular economy, such as sustainable sourcing, recycling and waste reduction, have also been recognised as critically important to provide enduring sustainability in the sector (Fontana et al., 2021; Zanoletti et al., 2021). Another essential aspect is the use of recycled content, such as reclaimed wood and wood waste, in engineered wood products, which helps to reduce the dependency on virgin timber and deforestation (Adefisan & McDonald, 2017; Amarasinghe et al., 2024). The use of green adhesives has also been emphasized; replacing conventional glues with bio-based and low-emission products has been heralded as a considerable improvement in controlling the emission of VOCs and enhancing indoor climate (Amato et al., 2020).

Additionally, the adoption of sustainability certification schemes, such as the FSC, has been indicated to greatly improve the ensured responsible procurement of raw materials, thereby enhancing forest stewardship and ecological conservation (Slastanova et al., 2021; Nygaard, 2023). Experts have stressed the need for these multifaceted integrated approaches, which include renewed technological advancements, resource-efficient operations and responsible sourcing, to enhance the sustainability of the EWP industry. Adoption of these innovations is hindered by obstacles such as inadequate funding, regulatory restrictions, extremely high specialization in sustainable forestry and green certifications and other forms of industry-specific unsustainable practices (Sikkema et al., 2017). Collaborative industry action, along with institutional framework strengthening and targeted policy advocacy, is critical to advancing sustainable EWP industry practices (Perlingeiro et al., 2020; Branca et al., 2021).

In Malaysia, some studies have sought to improve the sustainability of the EWP and mitigate the pressing environmental and resource issues. Sustainable forest management practices have been studied concerning certified burnout forests, such as those issued a certificate by the MTCC, ensuring sustainable practices of plantation management (Islam, 2010). Researchers are looking into the use of waste wood and biomass in place of virgin timber for EWP production because it decreases deforestation while simultaneously supporting a circular economy (Mokhtar et al., 2022). Other studies have focused on the energy efficiency of wood processing plants, reporting little to no use of renewable energy despite the potential to decrease carbon emissions and align with Malaysia's sustainability objectives (Razak & Abdulrazik, 2019). Eco-friendly engineered wood production, such as low-emission adhesives and the application of green production methods, has been identified as one of the major contributors to the country's engineered wood product's environmental footprint (Todorovic et al., 2021; Amarasinghe et al., 2024). The efforts outlined above demonstrate the reinforced, integrated, sustainable practices within the Malaysian engineered wood sector.

Initiatives and policies in promoting sustainable practices in the Malaysian wood processing industry

The Malaysian government, along with key industry stakeholders, has implemented a variety of policies and programmes that encourage sustainability in the wood industry. Table 1 shows that these efforts have some positive impact on the ecological issues as well as the sustainability of the wood processing industry in the long run.

Integrating waste reduction, energy-efficient technologies and responsible sourcing is vital for the advancement of sustainable practices in the wood processing industry. In Malaysia, the primary policy framework for SFM is the NFP, instituted in 1978 and revised in 1992 (NFP, 1992). The NFP focuses on resource forest development, ecologically sound conservation, biodiversity protection and increasing the environmental economic value derived from forests (Knoke, 2016). The NFP also prescribes forest stewardship, sustainable cutting practices, area replanting and conservation of the sanctuary's buffer zones. It is

Table 1
Initiatives and policies for sustainable practices in the wood processing industry.

Year	Initiatives	Level	Descriptions	Reference
1978	National Forestry Policy (NFP)	National	- The NFP was introduced in 1978 and revised in 1992, setting the guidelines for sustainable forest management in Malaysia. - This policy emphasises maintaining the ecological balance of forests while promoting sustainable utilisation of forest resources.	(Ministry of Energy and Natural Resources, 2021)
1993	Forest Stewardship Council (FSC) Certification	International	- The FSC certification system ensures sustainable forest management and responsible sourcing of raw materials, which requires forest operators to adhere to strict environmental, social and economic standards.	(Forest Stewardship Council, 2014)
2001	Malaysian Timber Certification Scheme (MTCS)	National	- MTCS is aimed at ensuring that Malaysia's timber industry adheres to sustainable harvesting practices and contributes to the conservation of the country's valuable forest resources. - The programme recognises MTCS for the Endorsement of Forest Certification (PEFC), a global standard for sustainable forest management.	(Block et al., 2021)
2009	National Green Technology Policy (NGTP)	National	- NGTP is a framework for promoting green technologies across various industries, including wood processing. - The policy encourages the use of energy-efficient machinery, the adoption of renewable energy sources and the reduction of waste.	(Ministry of Energy and KeTTHA, 2017)
2009	Green Building Index (GBI) Certification	National	- GBI is a certification system in Malaysia that encourages environmentally sustainable building practices. - This includes the use of environmentally friendly materials, such as sustainably sourced timber, in construction. - Through GBI certification, the government incentivises the construction industry to utilise engineered wood products that meet sustainability standards, fostering a market for eco-friendly wood products.	(Mun, 2009)
2009	Malaysia's Energy Efficiency and Conservation (EE&C) Master Plan and the Green Technology Financing Scheme (GTFS)	National	- The Malaysian government has promoted energy efficiency in the wood processing sector by providing financial incentives for companies that adopt energy-efficient technologies and practices. - The government encourages the use of renewable energy sources such as biomass, which can be generated from wood waste, reducing the sector's reliance on fossil fuels and decreasing carbon emissions.	(Ministry of Energy and KeTTHA, 2017)
2011	The Malaysian National Forest Stewardship Standard (NFSS)Sustainable Forest Management (SFM)	International	- National Forest Stewardship Standard (NFSS) to support Malaysia in advancing its sustainable forest management commitments, - SFM is an approach that includes a balanced management of forests for both timber and non-timber products while ensuring the protection of biodiversity and ecosystem services. - The government encourages logging companies to implement sustainable harvesting techniques and replanting efforts to maintain forest health and carbon sequestration capabilities.	(Moodley, 2022)

important to implement certifying bodies such as the FSC and the MTCS to guarantee that the lumber is sourced from well-preserved forests (MTCC, 2022; Murughan et al., 2024). The Malaysian government and other industry stakeholders have developed several critical policies aimed at improving sustainable practices in the wood processing industry. One of these policies is the MTCS, which strives to achieve sustainable management of forests through the certification of the areas and the responsible procurement of wood products.

As of 2021, over five million hectares of forest area certified by MTCS have aided in the sustainable procurement of timber (MTCC, 2021). In addition, Malaysia actively promotes the FSC certification, which is gaining greater acceptance, thus conforms to global environmental standards. The government launched the GTFS to promote greater sustainability by providing financial support for the implementation of energy-saving technologies and other green practices in the wood processing industry. The initiative has provided more than MYR 2.6 billion in loans and grants to support the adoption of green technologies (Moodley, 2022; Mohamad et al., 2024). These efforts focus on alleviating the environmental burden of the wood processing industry while enhancing sustainability.

Additionally, the industry can use biomass from wood scraps for renewables as well as implement energy-efficient technologies to lower their carbon footprint, a move made possible by the GTFS (MIDA, 2022). The circular economy is also fundamental as it encourages the recovery and reuse of wood waste such as sawdust and chips into value-added products, therefore minimising waste, enhancing reusability and reducing the carbon footprint of the industry (Khalid et al., 2025). The invention of new production technologies actively contributes to the environmental problem by allowing the use of alternative materials, such as bamboo, which reduces the dependence on timber (Patel et al., 2025). The literature suggests considerable work has been done to develop sustainable practices in engineered wood processing. However, there remains a gap in the literature (Inayat et al., 2018; Ramasamy, 2015), claiming that understanding the critical factors that motivate sustainability in EWP practices requires further research. There appears to be an absence of comprehensive evaluations aimed at the effectiveness of Malaysian EWP initiatives and an analysis of the potential barriers to their widespread use. Hence, this study aims to address the gap by investigating the challenges and proposing the main factors and solutions for the EWP industry's sustainable and eco-friendly practices in Malaysia (Figs. 1 and 2).

Research methodology

Research process

The mixed methods approach used in this study permits holistic data collection and supports the formation and validation of conceptual outcomes. It combines qualitative and quantitative methods and uses a questionnaire survey alongside semi-structured interviews as its two data sources (Hussain et al., 2020). The study employs an explanatory sequential design, beginning with the collection of quantitative information through cross-sectional survey questionnaires and concluding with qualitative data collection through structured interviews designed to clarify the quantitative findings (Taherdoost, 2016). This explanatory approach is supported by the fact that quantitative results, along with their analysis, provide a broad picture of the study problem. It is vital to collect qualitative data to better interpret or expand upon the more rigid numbers and figures (Schoonenboom & Johnson, 2017; Vedel et al., 2018; Toyon, 2021). Quantitative data were obtained using a cross-sectional survey regarding the current practices in the wood processing industry, as well as existing barriers and initiatives among the stakeholders involved. Thereafter, eleven (11) expert respondents were subjected to semi-structured interviews to capture professional perspectives on critical drivers, enabling factors and core strategies for effectively sustaining timber processing sustainability in the wood processing industry.

Questionnaire survey

The main study method used was a well-designed survey that contained both closed and open-ended questions. The goal of the survey was to obtain an authentic and credible understanding of each respondent's practices, level of awareness and acceptance of the innovations in the EWP industry. The key challenges and strategies for the survey were derived from the work of Ramasamy (2015) and Turan et al. (2017), along with other works on EWP. The results of this study have contributed to the development of a sustainability approach framework that concerns the familiarity of key strategies and barriers towards sustainability in the EWP industry in Malaysia. The incorporation of well-studied gaps proposed by Islam (2010) into the scope of this investigation adds depth to the insights gained. After the construction of the survey, five professionals, including lecturers and administrative personnel, were asked to complete pilot surveys before the distribution to test reliability and accuracy. The insights from the pilot study were used to refine the final questionnaire. The survey questionnaire was structured into three major parts, as follows:

a) Part A: Respondent profiles include information about the respondent's experience in the wood processing sector, age, years of work experience, engineered wood process and other relevant information.
b) Part B: Using a Likert scale, respondents were asked to rate their depth of understanding, familiarity with the sustainability concept and innovative approaches to the sustainability practices.
c) Part C: Participants were asked to prioritize innovative approaches and barriers for implementing sustainability in the EWP industry. A 20-item questionnaire with a five-point Likert scale ranging from "not important" to "extremely important" (the extent to which the respondents consider the following vital factor statements).

The main research instrument was a face-to-face survey using a well-structured questionnaire consisting of both closed and open-ended questions. This study used a non-probability sampling approach, specifically a criterion-based purposive sampling method, to select the participants. This method was chosen as it allows the selection of participants with specific characteristics and expertise relevant to engineered wood processing, ensuring that the data collected directly addresses the study objectives (Fasasi, 2024). The targeted respondents consisted of 67 industry personnel, including those from EWP manufacturers and producers, suppliers, researchers and government agencies involved in Malaysian engineering wood production. The list of EWP manufacturers and producers was procured through the Malaysian Wood Industries Association (MWIA).

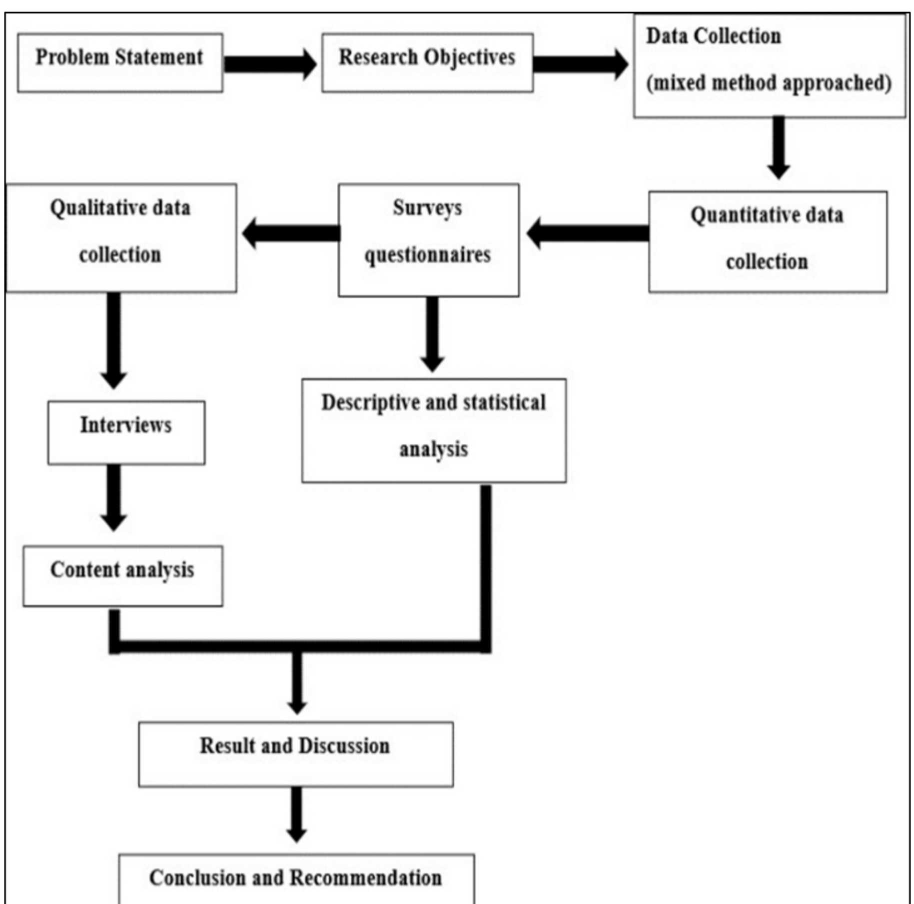

Fig. 1. Research process.

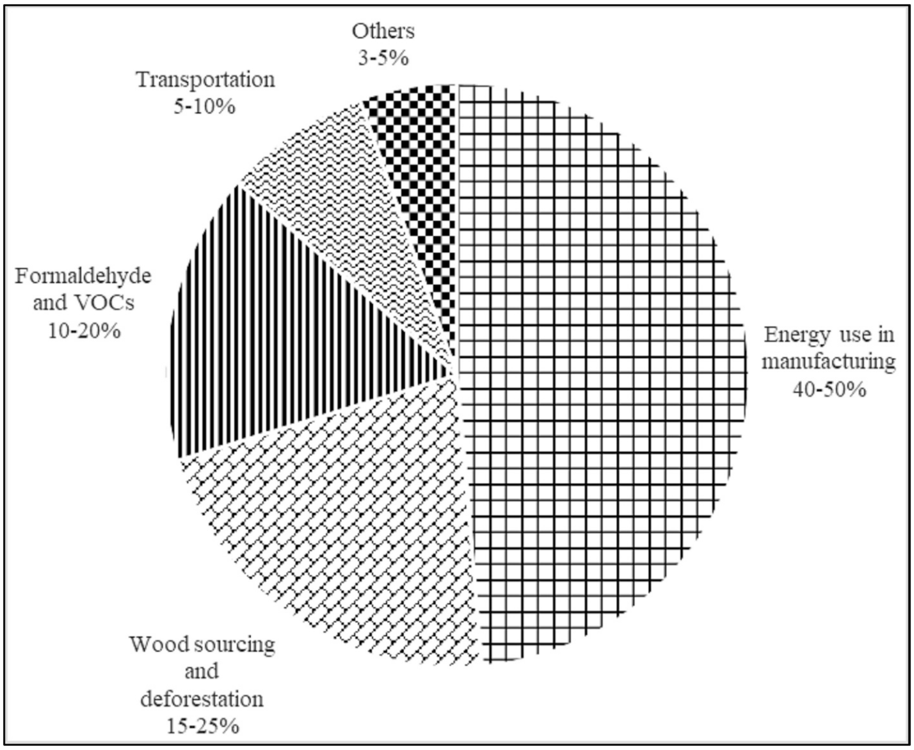

Fig. 2. Source of emissions generated from EWP production.

Interview

Expert insights were gathered regarding the main drivers and barriers to the successful adoption of sustainability practices within Malaysia's EWP industry through a semi-structured interview protocol. Purposeful sampling was applied to select eleven (11) respondents based on their extensive background in the EWP sector and research and development (R&D). The interviewees' designations include five (5) EWP manufacturers, three (3) officers from the Malaysian Timber Industry Board (MTIB), one (1) supplier and two (2) researchers. In-depth interviews were employed, as they allow for deeper exploration and validation of survey findings, providing contextual insights that enhance the credibility and robustness of the results (Osborne & Grant-Smith, 2021). The semi-structured questions were designed to allow interviewees to provide their expert knowledge on EWP as follows:

a) The main challenges that hinder the industry from regularly incorporating innovative approaches towards sustainability in the EWP industry.
b) The key drivers and strategies to adopt innovative approaches in enhancing sustainability in the EWP industry.
c) An open question for any other issues the interviewee wished to add or discuss.

Site Observations

Assessment of the adoption and practice of sustainability by five (5) EWP manufacturing companies was conducted by visiting each manufacturing company. Stakeholder views were obtained from structured interviews, while industry practices in the wood industry were assessed using a checklist and semi-structured questionnaires. Table 2 summarizes the five (5) selected EWP manufacturing plants included in the study. Site visits enabled the collection of information on plant profiles, location, year of company establishment, main areas of EWP production and production capacity.

Data analysis

For this analysis, descriptive analysis and descriptive statistics are used, which entail the percentage frequency distribution, mean (M), standard deviation (SD) and reliability test. Statistical analyses were conducted using IBM SPSS Statistics (IBM Corp., 2021). Systematic analysis was done through content analysis to review the data collected through interviews.

Reliability test

The reliability test using Cronbach's alpha coefficient was performed to measure the internal consistency of the survey's variables. For this study, the value of Cronbach's alpha is 0.875 (greater than 0.7), which means that the instrument used in measuring the variable is reliable (Ahmad et al., 2024).

Descriptive analysis

As the initial step in analysis, guiding investigation and simplification of data are some of the purposes that descriptive statistics serve. The availability of rich data, coupled with powerful computation techniques, has greatly advanced this domain of statistics (Yellapu, 2018). Descriptive analysis endeavors to provide a brief and clear summary of the most important highlights within a dataset so that users can understand its fundamental attributes without having to navigate complex statistical procedures (Cooksey, 2020; Dong, 2023).

Content analysis

Information analysis, a widely known technique, summarises data by categorically counting various traits as a type of qualitative research. For this research, conventional content analysis was applied. Utilizing the gathered data, the initial coding template was established (Hsieh & Shannon, 2005). That process required an exploratory approach where the assigned codes were rearranged and ordered until themes surfaced that represented the fundamental concepts and the intertwined relationships within the data (Yellapu, 2018). Thus, unprocessed narrative data, such as notes and audiotapes, were transformed into processed data called transcripts, which required manual transcription to extract the participants' responses.

Results and discussion

The section entails the findings and discussions on the survey questionnaire and interviews conducted in this study. The data analysis on participant feedback received from the survey questionnaires is presented in Section 4.1. The respondents' feedback on awareness, familiarity and practices on innovative concepts and sustainability concepts, key innovative approaches and challenges towards sustainability in EWP is presented in Section 4.1. Section 4.2 further presents the outcomes from in-depth interviews, which were conducted to validate and enrich the survey findings by providing deeper contextual insights.

Survey questionnaire finding

Table 3 shows the characteristics of respondents and their experience levels, which varied as 15 % reported having less than five years in the EWP industry, 42 % were in the 6-to-10-year band and 43 % had more than 11 years. It indicates that a large portion of the industry employees possess a good to very high level of experience in the EWP sector. The survey received responses from people in a variety of positions, such as 17 % were manufacturers, 10 % were suppliers, 36 % were operations like engineers, machine operators and production supervisors, 24 % were from government agencies dealing with wood and timber industries and 13 % were researchers.

Source of emissions from EWP production

Based on the assessment feedback from EWP manufacturers, energy use in manufacturing, specifically coal-fired electricity and equipment in use, constitutes the greatest source, approximately 40–50 %, of emissions when considering the equipment inventory record. The operator-reported value demonstrates the integrated emissions associated with engineered wood production, which is characterised as energy-intensive. Following this, respondents agreed that wood sourcing and deforestation, that is, the extraction of relatively raw materials, have a moderate impact with a contribution of 15–25 % of emissions. Furthermore, adhesives and formaldehyde derivatives can result in formaldehyde emissions in curing processes. Formaldehyde and VOCs also contribute a considerable fraction of emissions, estimated between 10 % and 20 %. Formed at rest and in transit, transportation emissions are also estimated as a smaller contributor, amounting to 5 % and do not go unnoticed in the context of the long-distance movement of raw materials and products. However, the range covered by logs encapsulated along with the orbital transportation utilised by them significantly impacts the overall carbon footprint; therefore, beyond the scope of the used vehicle defined, the emissions are also underrated. The remaining portion counted for 3 % of emissions, is likely attributable to end-of-life emissions arising when engineered wood products are disposed of in landfills or incinerated. Wood debris can lead to the displacement of uncontrolled emissions of volatile organic compounds and particulate matter into the free atmosphere. These findings are consistent with prior research that identifies manufacturing energy consumption as the dominant contributor to emissions in EWP production (Brueske et al., 2012; Loeffler et al., 2016; UNECE & FAO, 2021). Similarly, emissions from raw material sourcing (FAO, 2022), adhesive use (Goncalves et al., 2021) and transportation (Churkina, 2020) align with the reported ranges. Although relatively small, end-of-life emissions (~3%) have been highlighted in the literature as a potential source of uncontrolled release of VOCs and particulates (EPA, 2022; USEPA, 2023).

Table 2
Summary of five (5) EWP manufacturing plants.

No.	Plant Identification	Location	Year Established	Main EWP Products	Production Capacity (m^3/year)
1	Plant A	Klang, Selangor	2005	Laminated Veneer Lumber (LVL)	32,000
2	Plant B	Sungai Buloh, Selangor	2008	Glulam Beams	67,000
3	Plant C	Kuching, Sarawak	1998	Plywood	100,000
4	Plant D	Ipoh, Perak	2002	Laminated Flooring	25,000
5	Plant E	Kajang, Selangor	2010	Structural LVL, Glulam	84,000

Familiarity with innovative sustainability approaches in the EWP production process

Participants were queried on their knowledge concerning innovative approaches to sustainability within the EWP sector. In this study, 'very familiar' indicates respondents with extensive knowledge and experience and 'slightly familiar' refers to those with limited or basic exposure, while 'not familiar at all' represents respondents with no prior knowledge or experience of the innovative approaches to sustainability in the EWP production process. As illustrated in Fig. 3, over 75 % of participants reported recognizing major certification systems like FSC and MTCS. However, some only knew these systems operated at a more superficial level within the engineered wood context. While some of the respondents had some familiarity with innovations such as bio-based adhesives and smart wood technologies, a larger segment did not identify with being somewhat familiar with most of these advancements. Recognition of energy efficiency, recycling and renewable resource utilization for carbon footprint was acknowledged by half of the participants. Respondents were aware that engineered wood products reduce material waste and are less harmful to the environment than traditional materials. More than three-quarters of respondents were hardly aware of carbon sequestration and design for assembly, with only a quarter being regarded as very familiar with these innovative strategies.

Sustainable practice in EWP production processes

Fig. 4 shows the adoption of sustainability practices in their operations. 45 % of respondents say that they are reducing greenhouse gas emissions in their operations. 55 % of respondents indicated that they have adopted policies to conserve energy and 40 % of them have energy-efficient technologies in their production processes. 65 % of firms are using recyclable wood materials to produce EWP and are adopting waste minimization in their manufacturing processes. It incorporates reclaimed wood from construction, demolition and other industry processes. 50 % of respondents reported that they are implementing FSC

Table 3
Respondent Characteristics.

Respondents Characteristics	% of respondents (total respondents = 67)
Years of experience in EWP	
Less than 5 years	15
Between 6 and 10 years	42
11 years and above	43
Sector Designation	
Manufacturer	17
Supplier	10
Operation	36
Government	24
Researcher	13

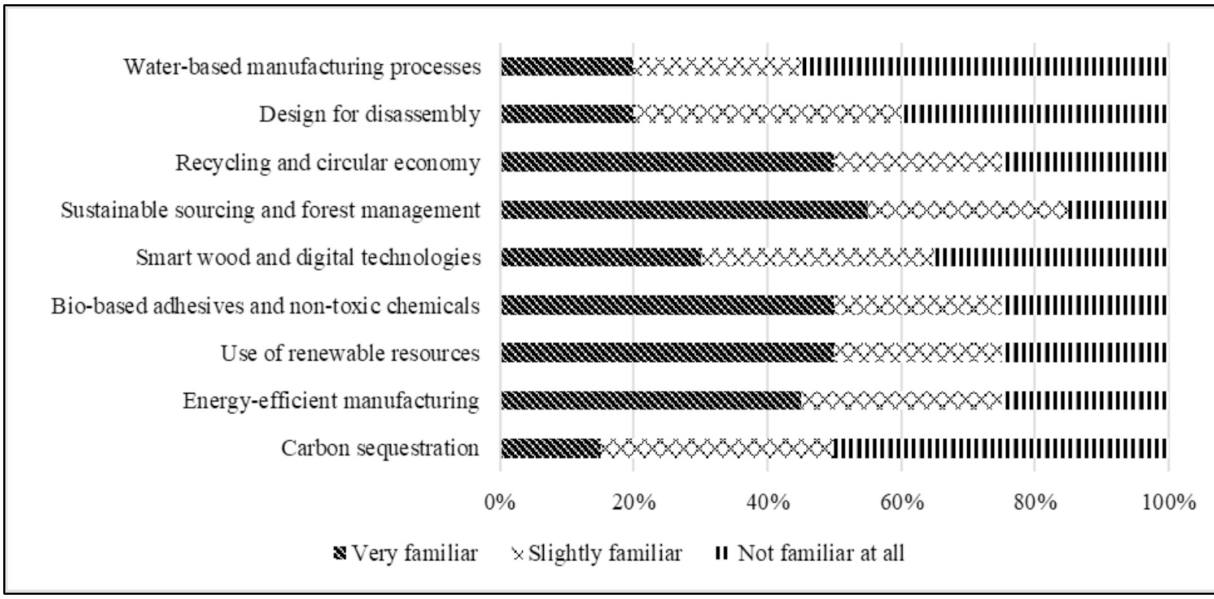

Fig. 3. Familiarity with innovative sustainability approaches.

and MTCS certification as one of the primary initiatives. 55 % of respondents reported using wood waste, including off-cutting engineered wood products such as sawdust and wood shavings, as feedstock for composite boards and using it as fuel in energy recovery systems. 55 % report that measures to reduce the air and water emissions generated by the company, including the installation of filtration and scrubber systems for controlling emissions from the chimneys of the processing plants, are active.

In comparison, only 35 % of respondents are incorporating solar power as a renewable energy source for their operations. 15 % of respondents report that they are using LCA in their process. The findings of this study supplement existing knowledge. Djunaidi et al. (2018) demonstrates that, while there is increasing commitment towards reaching an environmentally sustainable wood industry, the actual practice of mitigating and managing environmental impacts is strikingly low.

Innovative approaches to enhancing sustainability in EWP production

The participants were requested to express their views on EWP production, which includes 12 innovative strategies for improving sustainability in EWP and eight challenges to the implementation of these strategies. Tables 4 and 5 present the mean (M) and standard deviation (SD) statistical analysis for all facets identified in the preceding research. The descriptive surveys indicate that the M scores for nearly all characteristics pertinent to the critical factors of implementing sustainability in EWP exceed 3.00, suggesting that respondents received substantial feedback (Yadav & Kumar, 2022).

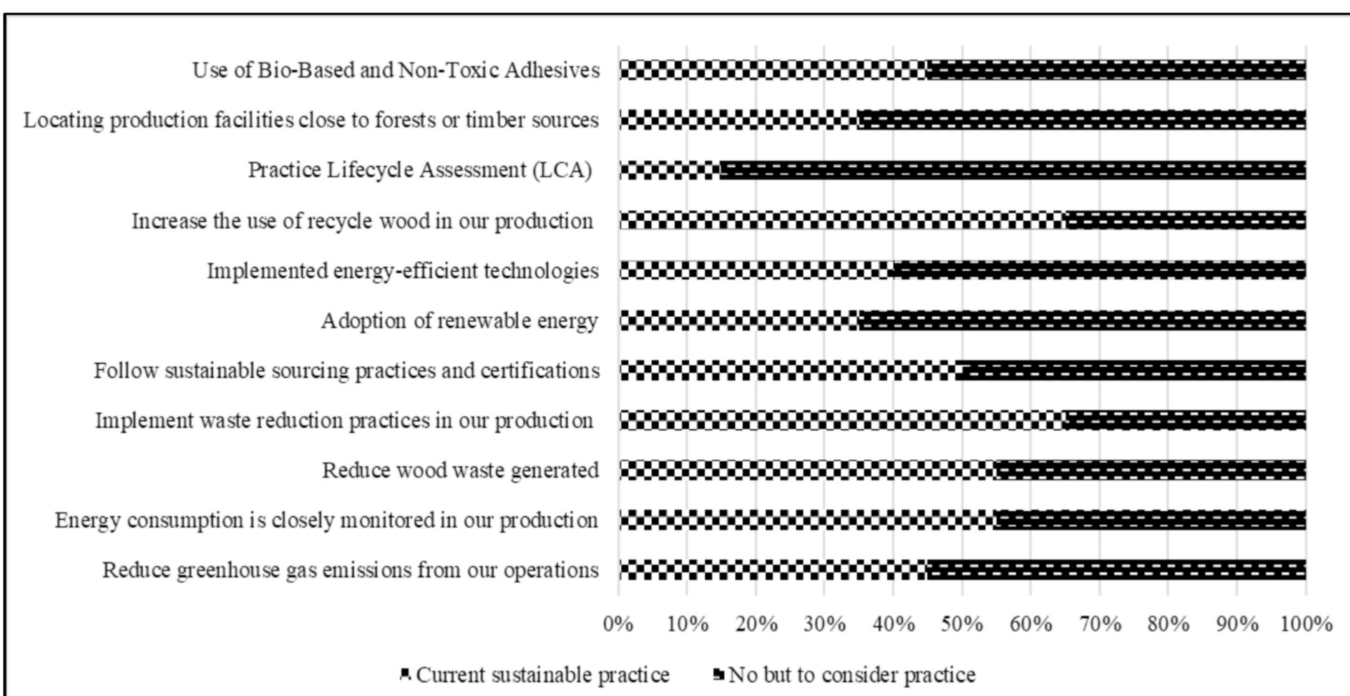

Fig. 4. Adoption of sustainability practices.

Table 4
Descriptive statistics of the mean and standard deviation for key innovative approaches.

Key Innovative Approaches	Mean	Std Deviation	Rank
Resource Management and Waste Reduction			
Implement waste reduction practices in production processes (e.g., recycling, reusing materials).	4.1630	1.2827	2
Reducing the amount of wood waste generated during production.	3.8487	1.3757	4
Recycled or reclaimed wood is a significant portion of the raw material in operations.	3.9147	1.2649	3
Use technological innovations to reduce waste and increase the efficiency of our resource management.	3.7437	1.3575	5
Energy Efficiency and Emissions Reduction			
Use energy-efficient technologies in the engineered wood processing industry.	3.6357	1.3427	6
Use renewable energy sources (e.g., solar, wind, biomass) in our production processes.	3.4362	1.4641	8
Reduce greenhouse gas emissions from our operations.	4.2737	1.5285	1
Closely monitor energy consumption and optimize energy use throughout production processes.	4.2737	1.0775	1
Technological Innovation and Adoption			
Innovation in production technologies (e.g., AI, automation) plays a key role in enhancing the sustainability of operations.	3.5464	1.4372	7
Invest in research and development to identify more sustainable materials and processes.	3.4937	1.4326	9
Circular Economy and Sustainable Sourcing			
Embraces circular economy principles (e.g., recycling, reuse and closed-loop systems) in operations.	3.9147	1.4763	3
Working with suppliers who follow sustainable sourcing practices and certifications (e.g., MTCS, FSC, PEFC).	3.6357	1.3642	6

Insights were collected from the respondents on how innovation can be applied to enhance sustainability in the production of EWP. As innovative approaches towards sustainability in EWP, the respondents noted 'reduce greenhouse gas emissions from operation' and 'closely monitor energy consumption and optimize energy use throughout production processes.' Besides, the 'reduction of waste in production processes was also considered an innovative approach, along with 'using recycled or reclaimed wood as a significant portion of the raw materials' and 'embracing circular economy principles.' Another noted innovative approach includes 'reducing the amount of wood waste generated during production' and 'applying technological innovations to waste and resource management,' thereby improving overall production efficiency. The innovative sustainability approaches identified by respondents include reducing greenhouse gas emissions, optimizing energy use, minimizing waste and utilizing recycled or reclaimed wood, which are consistent with global trends in sustainable wood product manufacturing. Prior studies highlight that energy efficiency and emissions reduction are central to decarbonising wood-based industries (Iwuanyanwu et al., 2024; Erdoğdu et al., 2025). Furthermore, technological innovations in resource and waste management are recognized as key enablers of sustainable production and competitiveness in the wood sector (Okugwu et al., 2023; Khan et al., 2025).

Barriers to adopting an innovative approach towards the sustainable EWP process

Respondents were asked to rate the barriers and the leading issue was 'the initial cost of implementing sustainable technologies. The high upfront cost of adopting sustainable technologies has been consistently identified as a major barrier in the wood and construction industries (Thirumal et al., 2024). 'Market competition and pressure for low-cost products' and 'sustainable options may be more expensive' were ranked second and third. 'Lack of knowledge and skilled workforce', 'introducing new and more sustainable materials or technologies may not easily integrate with existing manufacturing processes' are other vital issues chosen by respondents, followed by 'suppliers may not be ready to adopt sustainable materials or technologies.

Table 5
Descriptive statistics of the mean and standard deviation for the barriers in adopting innovative approaches in the EWP process.

Barriers	Mean	Std Deviation	Rank
The initial cost of implementing sustainable technologies is a major barrier to adopting them in our production processes.	3.9129	1.7525	1
Lack of knowledge and a skilled workforce are significant challenges in adopting innovative sustainability practices.	3.6719	1.8012	4
Regulatory or policy uncertainties hinder the adoption of sustainable practices in our industry.	3.4192	1.2864	6
Market competition and pressure for low-cost products limit our ability to invest in sustainable innovation.	3.8216	1.7571	2
Suppliers may not be ready to adopt sustainable materials or technologies.	3.5203	1.7613	5
Introducing new and more sustainable materials or technologies may not easily integrate with existing manufacturing processes, requiring significant adjustments or even redesigning equipment.	3.6719	1.7038	4
Sustainable options may be more expensive, which can deter consumers who are more focused on cost than on sustainability.	3.7357	1.7377	3
There may be gaps in the research and development required to make certain innovations more efficient or widely applicable in the engineered wood industry.	3.3624	1.7105	7

Interview findings

An interview-based approach with eleven (11) recognized experts in the field provided even more perspectives towards addressing barriers to the adoption of sustainability measures in EWP. As illustrated in Table 6, the arrangement of responses to identified ideas or problems was intended to refine understanding of the results from the in-depth interviews. These plans are designed to implement the participants' insights and enhance the efforts of the relevant stakeholders.

The respondents have proposed five (5) critical approaches toward sustainability strategies in EWP. These include the introduction of practices on 'government incentives and funding, research and development', education, training and program' and 'policy and regulatory enhancement', which were all noted as key EWP production drivers enabling innovative approaches and strategies towards EWP sustainability.

Discussion and Recommendation: Potential Path towards sustainability and a Way Forward in EWP production

EWP, including plywood, cross-laminated timber and oriented strand board, is becoming increasingly important in the construction and building sectors because of its sustainability attributes and versatility (Simeon et al., 2024). However, achieving long-term sustainability in the production of EWP requires a more comprehensive approach. These challenges have been categorised into four groups as the most prominent barriers to the industry's shift toward adopting sustainability-driven innovations, consisting of financial, technical, operational and institutional. Table 7 depicts the four strategic themes identified to further advances in sustainable innovations.

Situated within the global context of reduced deforestation and

Table 6
Respondent's opinion.

Key Strategies Themes	Respondents Opinion
Sustainable Practices	• Respondents agreed that sustainable practices require focusing on responsible sourcing, energy efficiency, waste reduction and environmentally friendly materials, including timber from FSC- and MTCS-certified forests. • Respondents emphasized that using energy-efficient technologies, renewable energy and heat recovery systems is crucial for reducing emissions and resource use in manufacturing. • Manufacturers should adopt bio-based adhesives (e.g., lignin, starch, tannins) and low-carbon, low-VOC materials, while using lifecycle assessment (LCA) to evaluate and improve product sustainability.
Government Incentives and Funding	• Respondents noted that government incentives: tax credits, grants and subsidies can ease the financial burden of adopting sustainable technologies, materials and waste-reduction practices.
Research and Development	• Most respondents agreed that research funding and tax breaks can support innovation, accelerating eco-friendly production techniques and alternative materials to reduce the industry's environmental footprint
Education and Training Program	• Most respondents agreed that education and awareness programs, along with stakeholder engagement, can promote low-carbon practices, improve training and encourage adoption of carbon management tools and green technologies
Policy and Regulatory Enhancement	• Respondents suggested that policies incentivizing certified sustainable materials, emission reductions and waste recycling, along with clear certification guidelines and strict formaldehyde standards, can better align the industry with global sustainability goals.

Table 7
Sustainability themes strategic.

Themes	Key Barriers	Key Strategies	Key Responsibility
T1: Financial	**High Initial Investment:** Sustainable technologies demand significant upfront costs for machinery, materials and training.	**Leverage Grants and Tax Incentives:** Many governments provide subsidies, grants, or tax incentives to offset the high initial costs of adopting sustainable practices and clean technologies.	Decision makers, government agencies and non-profit organisations
		Carbon Credits: Businesses can reduce emissions to earn carbon credit or join offset programs, creating revenue to support sustainability initiatives.	Government agencies, decision-makers and financing institution
	Market competition: Sustainably made EWPs face competition from cheaper and well-established materials.	**Obtain Sustainability Certifications and Eco-Labels:** Certifications and eco-labels can justify higher prices, helping recover sustainable investment costs through value-added marketing.	Manufacturers, suppliers, Certification Bodies, Environmental NGOs and environmental auditors
T2: Technical	**Integration with Existing Systems:** Existing systems may be incompatible with advanced technologies, requiring costly overhauls or new systems to integrate energy optimization and renewable sources.	**The phased approach to integration:** Manufacturers can retrofit systems and phase in renewable energy or efficient processes to cut costs without full infrastructure overhauls	Manufacturers, technology expert
T3: Institutional	**Industry Inertia:** The wood industry's reliance on conventional methods, coupled with resistance from manufacturers, suppliers and consumers, hinders the adoption of sustainable technologies.	**Incorporate Sustainability into the Business Model:** Embedding sustainability as a core value builds customer loyalty, strengthens brand reputation and boosts profitability.	Manufacturers, suppliers, government, consumers, Environmental NGOs and industry associations
		Educating Consumers and Stakeholders: Educating consumers and stakeholders fosters awareness, responsible consumption and appreciation of sustainable wood products.	Manufacturers, suppliers, government, consumers, Environmental NGOs and industry associations
	Regulatory and policy hurdles: Varying regulations and certification standards make compliance challenging for manufacturers.	**Advocacy and policy engagement:** Engage policymakers at all levels to advocate for clear, sustainability-focused regulations in the engineered wood industry.	Government agencies, decision-makers, regulatory bodies, manufacturers, suppliers, consumers, environmental NGOs and industry associations
		Participating in Industry Associations: Join industry associations and collaborate with stakeholders to develop science-based, sustainable policies.	
	Research and Development Gaps: Limited R&D investment and early-stage technology hinder progress in sustainable engineered wood.	**The multifaceted approach in R&D innovation:** Investment, collaboration, and sustainable practices are vital to drive innovation in materials, production, and environmental sustainability.	Government agencies, decision-makers, researchers, manufacturers, and suppliers
T4: Operational	**Supply chain issues:** Sourcing certified sustainable wood is challenging due to limited supply and high costs of programs like FSC.	**Source Sustainably Certified Materials**: Stricter timber sourcing rules make certified wood or alternatives like bamboo and recycled materials vital to avoid legal and reputational risks.	Government agencies, decision-makers, regulatory bodies, manufacturers, suppliers, consumers, environmental NGOs, and industry associations
	Lack of knowledge and skilled workforce: Adopting sustainable practices needs specialized skills, but a shortage of skilled labor hinders progress.	**Training and Development Upskill Programs:** Train employees in energy efficiency, waste reduction and responsible sourcing for sustainable EWP practices.	Manufacturers, suppliers, government, consumers, Environmental NGOs, and industry association

carbon footprint initiatives, Malaysia has maintained a vast forestry sector while recognizing the growing need for environmentally sustainable products. Regarding Malaysia's sustainable innovations in EWP production, the following strategies could be considered.

Firstly, addressing financial barriers through government incentives such as tax credits, subsidies and green bonds can significantly reduce the initial cost of sustainable technology adoption, particularly for SMEs. Prior studies highlight that financial mechanisms and grants play a pivotal role in encouraging companies to invest in green innovations by lowering entry costs (Fusillo et al., 2025; Sapar & Kusuma, 2025). Secondly, overcoming technical barriers requires greater investment in R&D and workforce training to build capacity for sustainable manufacturing systems. Research shows that investment in green R&D and skills development enhances a company's ability to integrate energy-efficient technologies and innovative production systems (Lagorio et al., 2024; Hossain et al., 2024). Thirdly, strengthening

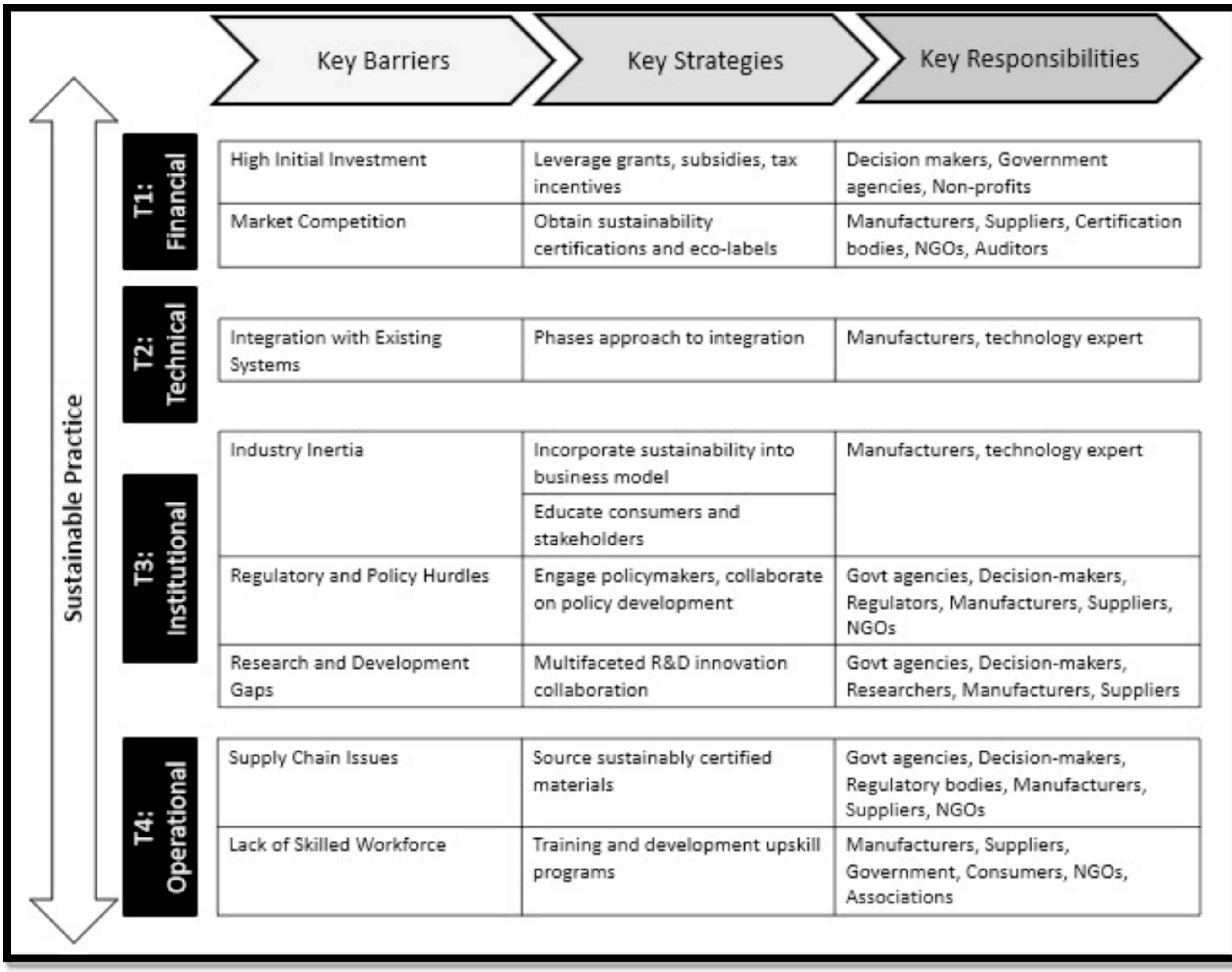

Fig. 5. Framework for shifting sustainability innovations in EWP.

institutional frameworks through stricter sustainability compliance and harmonised standards such as FSC and MTCS can provide industry-wide alignment. Literature suggests that clear regulatory frameworks and certification schemes improve credibility, competitiveness and long-term sustainability (Malovrh et al., 2019). Collaborative engagement with regulators, industry associations and environmental organizations further ensures that sustainability becomes standard rather than exceptional (Stocker et al., 2020). Finally, operational barriers can be addressed through the adoption of circular economic principles and improved supply chain traceability. Aligning with certified suppliers and adopting resource-efficient strategies not only ensures compliance but also leads to reduced waste, energy savings and long-term cost competitiveness (Sonar et al., 2024; Tramarico et al., 2025). These strategies reinforce that financial, technical, institutional and operational barriers must be approached in an integrated manner to achieve sustainable transformation in the EWP industry.

A combination of policies, innovations from the industry and financial support avenues is propelling Malaysia towards incorporating sustainability into the manufacturing of EWP. Comprehended from the study's findings, Fig. 5 illustrates a strategic approach framework towards shifting sustainability innovations in EWP. This framework addresses the specific themes that the industry faces and formulates actions to drive sustainability innovations. The outlined framework emphasises raising financial and economic worth, improving awareness, fostering institutional capacity development, credible policy advocacy, supply chain streamlining and knowledge and capability development. These proposed actions can transform profound financial, operational, institutional and technical barriers. By continuing to strengthen sustainability practices and incentivise innovation in the EWP sector, Malaysia can solidify its position as a leader in sustainable wood-based production, creating economic, social and environmental benefits.

Conclusion

The rising demand for EWP in Malaysia has intensified production activities, raising sustainability and environmental concerns. Unlike previous studies that often focus narrowly on either environmental practices or economic factors, this research uniquely integrates multiple dimensions of financial, technical, institutional and operational factors into a single framework, triangulated through stakeholder surveys, expert insights and site-level assessments. This holistic perspective not only captures the current state of sustainability practices but also provides a structured pathway for policy, industry and innovation alignment in Malaysia's EWP sector. Findings indicate moderate adoption of practices such as waste minimisation, recyclable wood use, energy conservation and emission control, while advanced measures like solar energy integration and LCA remain limited. Four key innovation pathways were identified: (i) resource management and waste reduction, (ii) energy efficiency and emissions reduction, (iii) technological innovation and adoption and (iv) circular economy and sustainable sourcing. Yet, the greatest constraints to better sustainability-driven innovations in EWP are budget and investment constraints, industry aversion to change, legislative and policy barriers, lack of adequate training, knowledge and expertise on sustainable forestry. The vision of a green Malaysia is hopeful but hinges on the full engagement and concerted effort of all parties toward a sustainable wood industry. Explicitly advancing financial and economic returns, scaling up institutional capacity expansion, garnering reputable policy advocacy and skill and knowledge formation present a highly significant comprehensive approach to expedite the sustainable leap in Malaysia's EWP industry. The construction of a framework integrating the four dimensions: financial, technical, institutional, operational and triangulating the results distinctly reveals all four aspects of the defined structure. By overcoming barriers and leveraging key pathways, Malaysia's EWP sector can advance sustainability, boost competitiveness and guide policy and industry innovation.

The study underscores significant opportunities for Malaysia's EWP sector, including alignment with the Twelfth Malaysia Plan 2021–2025 and SDGs (Goals 3, 11 and 13), growing domestic and international demand for sustainable wood products and potential for innovation-driven competitiveness. Future research should incorporate lifecycle assessment data and engage a broader range of stakeholders to refine sustainability strategies. By leveraging identified pathways and addressing barriers, Malaysia's EWP industry can advance toward a low-carbon, competitive and environmentally responsible future, supporting both operational efficiency and sustainable growth.

CRediT authorship contribution statement

Nur Kamaliah Mustaffa: Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Zakiah Ahmad:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Zadariana Jamil:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Formal analysis, Conceptualization. **Emmanuel Appiah-Kubi:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization. **Nurul Atiqah Mukhtar:** Writing – review & editing, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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