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Feasibility assessment of agricultural waste-derived bio-based cushioning materials for sustainable transportation packaging applications

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ABSTRACT

The growth of e-commerce and transportation activities has increased the demand for protective packaging materials and raised awareness of the environmental impacts of petroleum-based cushioning products. Based on the current literature, agricultural biomass residues represent a renewable option for developing sustainable packaging systems that align with circular economy and green logistics principles. This study aimed to evaluate the potential of developing bio-based cushioning materials from bamboo residues and coconut husk fibers for transportation packaging applications. A structured experimental feasibility framework was used to assess cushioning performance under simulated transportation conditions. Prototype cushioning sheets were developed using different material formulations and compared through drop impact testing. Under controlled impact conditions, cushioning performance was evaluated based on product protection and the occurrence of fractures. The results demonstrated that the bio-based cushioning materials achieved a high product protection rate. Only one fracture event was observed during 40 experimental cycles, resulting in a product protection rate of 97.5%. Under the conditions studied, the different material formulations showed varying cushioning performance. In addition to their protective properties, these materials have potential for agricultural waste valorization and reducing the use of petroleum-based packaging materials. The findings indicate that bamboo residues and coconut husk fibers are promising sustainable materials for transportation cushioning applications and support their potential use in the circular economy and green logistics.

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1. Introduction

Transportation and logistics systems play a critical role in product distribution and global supply chain operations, particularly in the rapidly expanding digital economy and e-commerce sectors. Increasing transport and distribution activities, specifically in the e-commerce industry, international trade, and time-critical delivery systems, have also significantly boosted the demand for transportation packaging materials. Transportation packaging is critical to avoid physical harm to products during mobility, transportation, palletization, and multimodal logistics tasks (Parfenov et al., 2021). Product damage due to transportation has become a core issue of modern logistics and supply chain services. However, effective protective packaging systems can be utilized to reduce product losses as well as reverse logistics costs and improve operational efficiency, hence enhancing service in transportation and the transport and distribution processes. Therefore, within a green logistics system, increasing attention has been paid to developing eco-friendly transport packaging that assures both product and environmental sustainability (Ahmed et al., 2018; Hao et al., 2019).

Among all transport packaging materials, the structural material of cushioning used in transportation packaging systems is a vital component for cushioning effectiveness, vibration reduction, and external load management of logistics operations. Traditional cushioning materials commonly used in logistics applications are typically

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expanded polystyrene (EPS), PU foam, bubble wrap, and petroleum-based polymeric materials. These all afford excellent product protection performance, are lightweight, and have high mass production potential. However, most synthetic cushioning products are made with non-renewable fossil resources and are therefore non-biodegradable, making them responsible for the majority of long-term environmental pollution and plastic waste accumulation (Adak et al., 2025). Plastic waste, especially packaging-related plastic, has become a significant global environmental concern, with packaging waste produced in modern economies accounting for over one-third of the total plastic waste. The plastic waste generated by human systems adds to the massive environmental cost, including microplastic contamination in aquatic ecosystems and the formation of marine pollution, alongside greenhouse gas emissions that derive from the processing and disposal of plastic. Therefore, the development of bio-based packaging alternatives is emerging as an area of increasing interest to both producers and researchers (Yu and Singh, 2023).

One promising approach to addressing this is the development of bio-based packaging materials derived from renewable resources. These materials typically have lower environmental impacts and better biodegradability capacity than synthetic polymers. Such an approach can be more aligned with the principles of the circular economy, through the efficient use of resources, waste minimization systems, and recycling of materials, while also supporting green logistics strategies, which emphasize the minimization of environmental impacts throughout the logistics process (Kittichotsatsawat et al., 2025). Due to their low density, desirable cushioning performance, biodegradable properties, and energy absorption capability, natural fibers such as bamboo, jute, hemp, and coconut have recently gained wide interest in research. Furthermore, natural fiber-based materials consume significantly less energy in the manufacturing process than synthetic fabrics or fiber composites themselves (Reichert et al., 2020). An extensive agricultural biomass resource base is maintained in Thailand, mainly composed of agricultural residues obtained in processing and production stages, which consist of bamboo residues, coconut husks, rice straw, and sugarcane bagasse. These materials are often treated as waste and disposed of through open burning or landfilling, resulting in environmental impacts and resource losses. However, the production of value-added products from agricultural wastes, such as packaging and cushioning substances, has the potential to reduce agricultural waste treatment, enhance the use of resources, and underpin sustainable development (Jusakulvijit et al., 2021).

Bamboo residues and coconut husk waste are abundantly available in many agricultural regions of Thailand, providing a potential feedstock for renewable cushioning material development. Bamboo exhibits a high strength-to-weight ratio and excellent structural rigidity, while coconut husk fibers display beneficial elasticity and cushioning behavior. Accordingly, the integration of these biomass materials has great potential to develop renewable cushioning materials with good protective properties (Nechita and Năstac, 2022). Additionally, both bamboo residues and coconut husk fibers were chosen according to natural resource availability and engineering considerations. Such agricultural residues are widely produced in Thailand and are often underutilized or disposed of as low-value waste. Bamboo has a high structural rigidity and a favorable strength-to-weight ratio, while coconut husk fibers have good elasticity with effects on energy absorption characteristics. These two biomass resources have complementary properties, which position them as potential candidates to implement bio-based cushioning materials. This study was not aimed at assessing the optimal agricultural residue to be created from available biomass types, but rather to assess the engineering potential of using one promising combination of agricultural wastes in the application of sustainable transport packages.

In recent years, growing attention has been directed toward natural fiber-based packaging materials. However, notwithstanding the growing popularity of natural fiber packaging systems, some research gaps still exist (Pulikkalparambil et al., 2023). First, the majority of studies carried out in the past addressed single fiber systems, and relatively little research was conducted on hybrid cushioning materials derived from agricultural waste. Second, previous studies mainly focused on the mechanical characterization of the materials, while there have been relatively few studies evaluating the cushioning behavior under simulated transportation conditions; thirdly, the sustainable use of bamboo residues and coconut husk fibers as cushioning materials for transportation packaging is largely unexplored. These limitations indicate the need for further investigation of agricultural waste-derived cushioning materials for transportation packaging applications.

To the best of the authors' knowledge, unlike previous works focused on the mechanical testing of natural fiber composites, this research aimed to assess the practical feasibility of applying cushioning materials obtained from agricultural wastes in transportation packaging applications was aimed at. The unique element of this study was to combine agricultural waste valorization, Design of Experiments (DOE)-based feasibility assessment, testing of transportation effects under simulated logistics conditions, and sustainability analysis under a single application perspective. This holistic perspective contributes to the green logistics and circular economy execution and presents practical proof-of-concept for renewable farm residues in sustainable transportation packaging systems (Kittichotsatsawat et al., 2024). This study is, therefore, a preliminary engineering study of bio-based cushioning materials from agricultural waste

for sustainable transportation packaging. The results contribute practical insights that have the potential to support agricultural waste valorization, environmentally friendly packaging systems, and the operational application of green logistics and circular economy principles (Kittichotsatsawat et al., 2021).

2. Literature review

2.1. Circular economy and sustainable packaging

A circular economy is an industrial and economic model based on sustainable production, where resources are used effectively, waste and materials are recycled, and the environmental footprint is reduced from start to finish throughout the product lifecycle (George et al., 2015; Korhonen et al., 2018). As with the 'take–make–dispose' model in a linear economy, the circular economy emphasizes more regenerative and restorative resource utilization, allowing waste and use to be minimized and its long-term adverse environmental impacts to be remedied (Rashid and Malik, 2023).

In the transport sector, logistics industries, and other industries, protective materials that minimize plastic waste generation and reduce dependence on petroleum-based polymers and utilize petroleum-derived polymers have recently become a consideration (Rajendran et al., 2025). With e-commerce, demands for transportation, distribution, and other activities have increased, and packaging waste has become a major environmental concern. Therefore, eco-friendly options such as biodegradable and renewable packaging materials have been emphasized in eco-friendly logistics and green supply chain strategies (Ali et al., 2024).

2.2. Natural fiber composites for cushioning applications

Natural fiber composites have attracted increasing research attention as potential alternatives to conventional synthetic cushioning materials (Begum and Islam, 2013; Pandey et al., 2010; Pickering and Le, 2016). Bamboo, jute, hemp, flax, sisal, coconut, and other natural fibers are advantageous as they are low-density, biodegradable, renewable, and capable of absorbing impacts (Zhang et al., 2025). Natural fibers have been found to add increased cushioning performance, mechanical stability, and environmental protection to bio-based materials in previous research work. Elmessiry et al. (2025) found that the incorporation of natural fibers enhanced the flexural strength and the impact-absorbing properties, increasing biodegradability attributes at the same time, while Liu (2024) reported favorable biodegradation characteristics and cushioning performance and cushioning behaviors under controlled environmental conditions. Moreover, among performance advantages that are mechanical in nature, natural fiber materials have exhibited strong potential for cushioning applications and agricultural waste valorization strategies. These findings suggest that natural fibers can simultaneously enhance cushioning performance and environmental sustainability. However, most studies have focused on laboratory-scale mechanical testing, while transportation impact performance remains insufficiently investigated.

Residual agricultural biomass such as bamboo waste and coconut husk fibers can also be utilized to reduce agricultural waste disposal and promote circular economy and green logistics practices (Jayaprakash et al., 2022). However, the literature review only addresses single-fiber composite systems or protective capability evaluation, and relatively little focus has been placed on the evaluation of hybrid agricultural waste-based cushioning materials under transportation impact conditions pertaining to logistics applications.

2.3. Experimental evaluation approaches in bio-based material development

Experimental design and evaluation approaches have been widely employed to investigate the performance of bio-based materials under controlled conditions. Compared with traditional one-factor-at-a-time approaches, structured experimental evaluation methods enhance experimental efficiency and provide a systematic basis for investigating material behavior (Antony, 2003). The application of DOE methods for bio-based material processing and composite development in more advanced applications has been well-documented in some prior works, mainly within the Taguchi method and response surface methodology (RSM) (Murugan et al., 2025).

Similarly, Shojaei et al. (2021) indicated that Taguchi orthogonal array methods greatly reduced the experimental trials needed and improved experimental efficiency during the material design stages. Patel et al. (2024) also proposed that Taguchi approaches are especially well-suited for early-stage feasibility studies and factor screening efforts, while RSM is more appropriate for advanced performance modeling and in-depth optimization studies. While experimental evaluation methodologies have been widely used in the domain of material engineering, few studies have integrated EFS-based experimental evaluation with renewable cushioning material development in the context of transportation packaging applications based on natural fibers derived from agricultural waste (Shahdan et al., 2023). Based on the reviewed literature, several research gaps can be identified. Most previous studies focused on single-fiber materials and general mechanical characterization, while limited attention has been given to hybrid agricultural waste-derived cushioning materials and their performance under transportation impact conditions.

Furthermore, the use of bamboo residues and coconut husk fibers as cushioning materials for sustainable transportation packaging remains underexplored. Therefore, this study investigates the feasibility of developing bio-based cushioning materials derived from these agricultural residues and evaluates their cushioning performance under simulated transportation conditions.

3. Methodology

An experimental research framework was utilized to create and evaluate bio-based cushioning materials made from bamboo residues and coconut husk fibers, aimed at promoting sustainable packaging solutions for transportation.

3.1. Raw material preparation and experimental design

The raw materials were bamboo residues and coconut husk fibers obtained from Ang Thong Province, Thailand. Before the experiments, both raw materials were cleaned, dried, and mechanically processed to the appropriate fiber sizes. Tapioca starch was considered a natural binder, and the fiber surface was treated with a sodium hydroxide (NaOH) solution at about 5 wt.% solution to enhance fiber adhesion and interfacial bonding. A structured experimental evaluation framework was employed to investigate the influence of material composition and thickness on cushioning performance and product protection capability. The primary response variable was the transportation impact outcome, which was evaluated based on fracture and non-fracture observations during drop impact testing. Product protection capability under a simulated transportation environment is evaluated from the response. From Table 1, it is seen that, in order to evaluate the influence of material composition and structural parameters on cushioning performance, two experimental factors were selected in this study, namely coconut fiber composition and material thickness.

Table 1: Experimental factors and levels

Factor	Symbol	Levels
Coconut fiber (%)	A	30, 50, 70
Thickness (mm)	B	10, 12, 15

According to Table 2, the amount of bamboo fiber was changed in all formulations to ensure consistency in the total fiber content. The coconut fiber composition and material thickness were then evaluated using a 3^2 full factorial design to infer the factors influencing cushioning.

3.2. Fabrication of bio-based cushioning materials

The fibers were prepared and incorporated using a tapioca starch binder according to the established formulations. Fiber treatment was carried out using a sodium hydroxide solution to improve fiber adhesion and interfacial bonding within the composite structure (2 hours). The mixed materials were subsequently molded and compressed under the same forming conditions for the experimental samples. The fabricated cushioning sheets were subsequently dried under controlled conditions to lower moisture content and make them more dimensionally stable before testing

Table 2: Experimental design matrix

Run	Coconut fiber (%)	Thickness (mm)	Response variable
1	30	10	Transportation impact observation
2	30	12	
3	30	15	
4	50	10	
5	50	12	
6	50	15	
7	70	10	
8	70	12	
9	70	15	

3.3. Mechanical and impact performance testing

The engineered cushioning materials were evaluated through mechanical and transportation impact performance testing. Drop impact testing was conducted in accordance with the general principles of ASTM D5276 to assess transportation protection capability under simulated laboratory conditions (Aafrin et al., 2025; Kassim et al., 2023; Ralisnawati et al., 2025). Ceramic cups were employed as fragile product simulators because of their high sensitivity to impact damage. Experimental testing involved controlled free-fall drops at predetermined transportation impact conditions under consistent testing configurations.

The selected drop heights of 1, 2, and 3 m were intended to represent progressively increasing transportation impact conditions for comparative engineering evaluation under controlled laboratory conditions. These heights were selected to compare the cushioning performance of different material formulations rather than to reproduce a specific logistics distribution scenario. Since actual transportation environments involve a wide range of handling and distribution conditions, the selected drop heights provide a practical laboratory-based framework for preliminary feasibility evaluation of bio-based cushioning materials. Future studies should incorporate standardized transportation simulation protocols, vibration testing, and industrial distribution trials to further validate the practical applicability of the developed cushioning materials. The potential energy resulting from gravity, as outlined in Eq. 1, was used to compute the theoretical impact energy produced during drop testing.

$$E = mgh \quad (1)$$

where, E is the impact energy J, m is the mass of the dropped object (kg), g is the gravitational acceleration (9.81 m/s^2), and h is the drop height (m).

Protective performance was evaluated in terms of transportation damage prevention, deformation characteristics, and protective capability behavior. The dimensional measurements, material thickness, and physical appearance after testing were recorded for cushioning performance evaluation under the investigated conditions. This study focused primarily on assessing the cushioning feasibility under simulated transportation impact conditions as a preliminary engineering study of sustainable logistics packaging applications.

3.4. Statistical analysis and evaluation

Descriptive statistics, trend analysis, and graphical evaluation methods were used to analyze experimental data. Fracture occurrence and product protection performance were compared across different material formulations and thickness levels to identify favorable cushioning configurations. Instead of predictive statistical modeling, the analysis was primarily concerned with assessing cushioning feasibility and transportation protection capability.

3.5. Validation and reliability assessment

The reliability and authenticity of the experimental data were guaranteed by creating all samples under uniform processing conditions and evaluating them with consistent equipment and methodologies. Materials were obtained from the same source to reduce variability in material properties. The experimental results were verified through repeated experimental trials and confirmation testing of selected formulations. Experimentally, the testing procedure was adapted to the international transportation packaging testing standards, which enhanced experimental credibility and practical compatibility in sustainable logistics systems. The fabricated cushioning materials were evaluated in terms of environmentally responsible transportation packaging, circular economy, agricultural waste valorization, and sustainable supply chain operations.

4. Results

4.1. Experimental results

An assessment of the performance of the created bio-based cushioning materials was carried out by analyzing their capacity to absorb impacts and reduce product damage during transportation and logistics processes, utilizing drop-impact testing methods. It was verified from the empirical findings that the cushioning materials composed of bamboo residues and coconut husk fibers provide various transportation protection and are effective, depending on the composition of the material and the mixing ratio. The drop-impact tests were performed at the impact conditions of transportation, being 1, 2, and 3 meters. After each drop test, the packaging box was opened, and the internal damage conditions were analyzed and assessed. Photographic documentation and detailed observations were systematically recorded for all experimental trials. The experimental results were in accordance with the guidelines regarding validity and reliability in all formulations since each of the samples underwent triplicate testing. The results obtained are presented in Table 3.

As per Table 3, the 100% fiber-bamboo-based cushioning material also revealed good structural rigidity and adequacy due to the fibrous nature of bamboo fibers and its high stability and high strength-to-weight performance. The stable structure was confirmed in this formulation, and cushioning effectiveness was observed during drop impact testing. In the cushioning material made entirely from coconut husk fibers, effective impact mitigation performance was attained due to the natural flexibility of the fibers. As a result, cushioning behavior was observed during drop impact testing (Nechita and Năstac, 2022; Zhang et al., 2025). In addition, cushioning performance under impact loading was positively affected by the use of coconut fibers on the substrate. Analysis of hybrid formulations indicated that the ratio of bamboo residue to coconut husk fiber contributed to cushioning effectiveness. The 50:50 configuration provided only moderate protection, along with localized structural instability and minor product damage when the drop was low-impact. According to the material analysis, the distribution of fibers was not sufficient to maintain the structural continuity and strength required for high-impact resistance. However, 70:30 and 30:70 formulations achieved superior protective effects. The combination of the structural strength of bamboo fibers and the flexibility characteristics of coconut fibers in these hybrid composites indicated efficient transportation impact resistance and improved product protection performance, providing excellent cushioning performance.

The developed cushioning materials suggested adequate cushioning behavior and product protection during drop impact tests. In the field of sustainable packaging applications, both the cushioning behavior and cushioning behavior of agricultural waste-based and cellulose-based cushioning are comparable in previous studies (Nechita and Năstac, 2022). The resulting cushioning materials implied favorable product protection performance under the investigated transportation impact conditions. These findings point out the potential of utilizing agricultural waste-derived cushioning materials as sustainable alternatives for transportation packaging applications. They not only reflect the potential use of agricultural waste cushioning material but also the practical utilization of agricultural waste-derived cushioning material in sustainable transportation packaging systems and sustainable logistics operations.

Table 3: Impact resistance test results

Sample type	Transportation impact condition	Test no.	Test result
Formula 1: Bamboo residue (100%)	1	1	No fracture observed
		2	
		3	
	2	1	
		2	
		3	
	3	1	
		2	
		3	
Formula 2: Coconut husk fiber (100%)	1	1	
		2	
		3	
	2	1	
		2	
		3	
	3	1	
		2	
		3	
Formula 3: Bamboo residue and coconut husk fiber (50:50)	1	1	Fracture observed
		2	-
		3	-
	2	1	-
		2	-
		3	
	3	1	
		2	
		3	
Formula 4: Bamboo residue and coconut husk fiber (70:30)	1	1	No fracture observed
		2	
		3	
	2	1	
		2	
		3	
	3	1	
		2	
		3	
Formula 5: Bamboo residue and coconut husk fiber (30:70)	1	1	
		2	
		3	
	2	1	
		2	
		3	
	3	1	
		2	
		3	

4.2. Experimental performance analysis

4.2.1. Graphical analysis

The influences of coconut fiber and bamboo fiber ratios on transportation impact response and cushioning test outcomes were examined using Pareto charts, main effects plots, interaction plots, and data distribution charts generated from Minitab. The interaction plot for transportation impact response analysis is shown in Fig. 1.

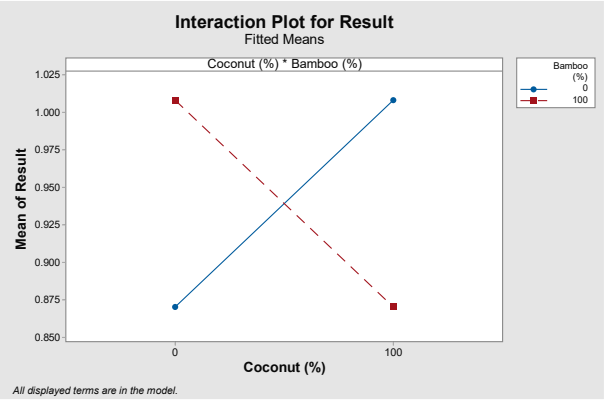


Fig. 1: Exploratory interaction plot for transportation impact response

The graphical evaluation shown in Fig. 1 suggests that no clear performance differences were observed among the investigated material compositions under the tested conditions. Only one fracture event was observed in the 40 experimental trials, demonstrating that the cushioning performance behavior of the developed bio-based cushioning materials was satisfactory. Formulations containing coconut fibers exhibited favorable cushioning performance under the investigated conditions; bamboo fiber proportions appeared to contribute to satisfactory structural stability under the investigated conditions. However, the relatively low variability of the fracture-based response may have contributed to the reduction in the sensitivity of the existing evaluation framework. Further research should be done on the addition of quantitative response variables to enhance the statistical robustness and engineering interpretation of cushioning performance.

Experimental variables of the present study were categorized as independent and dependent variables to assess the cushioning effectiveness of the developed bio-based cushioning substrates. The independent variables were defined as ratios of coconut fibers and bamboo fibers, which were

investigated at five levels: 0%, 30%, 50%, 70%, and 100%. Tapioca starch was maintained at a constant ratio of 50% and used as the binding agent. In addition, material thicknesses of 10 mm, 12 mm, and 15 mm, along with three transportation impact conditions, were considered as drop impact conditions to capture various transportation impact scenarios. The dependent variable was the drop impact test result, which was defined by the state of the ceramic cup after impact testing. We then assigned "non-fracture" (0), a value that indicated that a fracture was not detected, and "Fracture observed" (1) when a fracture occurred. The experimental data were then subjected to statistical analysis to explore comparisons between the cushioning performance of the respective material formulations (Table 4).

Table 4: Summary of fracture test results by material formulation

Sample	Coconut (%)	Bamboo (%)	Starch (%)	Thickness (mm)	Number of tests	Number of fractures	Fracture rate (%)
1	70	30	50	12	9	0	0.0%
2	30	70	50	15	9	0	0.0%
3	50	50	50	10	4	1	25.0%
4	100	0	50	10	9	0	0.0%
5	0	100	50	10	9	0	0.0%

As seen in Table 4, the developed bio-based cushioning materials were tested in drop impact test conditions during simulated transportation. Forty separate experimental procedures conducted using ceramic cups showcased various cushioning material formulations and thicknesses under transportation impact conditions. In general, the developed cushioning materials were successful in protecting packaged products against transportation-related damage. In total, 40 work trials were carried out, and 39 tests (97.5%) prevented fractures of ceramic cups. One fracture, 2.5% of all tests, was observed. The resulting product protection rate of 97.5% provides practical evidence supporting the feasibility of the developed cushioning materials for transportation packaging applications. By analyzing such results from the studies, it has been found that the developed cushioning materials can be readily implemented for use in transportation packaging, demonstrating that the product provides good protection in the studied environment. These findings confirm that bamboo residues and coconut husk fibers can serve as bio-based cushioning materials when combined with tapioca starch, which acts as a natural binder. Hence, the materials created show substantial potential for sustainable packaging and transport applications.

4.2.2. Main effects

At the point of use, analysis of fiber composition ratios suggested that the cushioning behavior of the developed materials may be associated with the proportions of coconut and bamboo fibers. As an example, a ceramic cup fracture was prevented in all nine experimental tests of Sample 1, which was made with 70% coconut fiber and 30% bamboo fibers in a 12 mm compound material, yielding a fracture rate of 0%. This observation suggests that formulations containing higher proportions of coconut fiber exhibited protective capability under the investigated conditions (Jitkokkruad et al., 2023). Similarly, regarding Sample 2 (30% coconut fibers, 70% bamboo fibers), a 15 mm medium, no product damage was detected in all nine experiments of the material. This formulation also showed product damage prevention performance under the investigated conditions. By contrast, the fracture rate was close to 25% in Sample 3 (coconut fibers: bamboo fibers, 50:50, 10 mm thickness), which experienced a first fracture at Transportation Impact Condition 2. This observation may indicate that the 50:50 fiber ratio was less effective in maintaining structural continuity under the investigated impact conditions. In Samples 4 and 5 (100% coconut fibers and 100% bamboo fibers (material thickness: 10 mm), during the research period, no ceramic cup fracture occurred. This result suggests that both single-fiber formulations provided protective performance under the investigated transportation impact conditions. Nevertheless, these observations should be interpreted with caution because material thickness was not constant across all formulations and may have contributed to the observed differences in cushioning performance (Tomin and Kmetty, 2022).

The findings suggested that thicker cushioning material had a higher protective product effect, as well as improved satisfactory cushioning performance, and the thickness was chosen as an important factor for the protective effect (Koinig et al., 2022). On the whole, it was found that the thicker cushioning material had the best satisfactory cushioning performance, and that bulk material volume with large internal void structures resulted in lower impact power. It was also noted that, except for one fracture in the 10 mm thickness of the cushioning materials (Samples 3, 4, and 5), a total of one fracture of 10 mm thickness was observed, representing approximately 3.6% (28 testing cases). Fracture was observed only in Sample 3 (consisting of coconut fiber and bamboo fiber with similar percentages). In contrast, no fracture was observed for cushioning material of thickness 12 mm in Sample 1. This evidence suggests an increase in product protection efficiency with material thickness, followed by a marked reduction in product damage probability with a significant increase in material thickness. Based on Sample 2 with 15 mm thick cushioning material, it shows that zero fractures occurred under the studied conditions and overall material performance was better from

the thickness perspective in the same test conditions. All controlled drop impacts in a thickness range of this type had packaging protection performance.

As summarized in Table 5, the results indicated a general tendency for higher transportation impact conditions to increase the likelihood of product damage because more impact energy was produced during the test (Dill et al., 2020). The lowest impact condition (Transportation Impact Condition 1) revealed no ceramic cup fractures in all 15 experimental runs, achieving a 0% fracture rate. The moderate impact condition, Transportation Impact Condition 2, yielded one fracture event out of 15 tests, with a fracture rate of about 6.7%. Sample 3, composed of equal amounts of coconut fibers and bamboo fibers and with a material thickness of 10 mm, exhibited fracture. Notably, the highest impact condition of Transportation Impact Condition 3, which was investigated in this study, showed no ceramic cup fractures in all 12 experimental trials. This result suggests that the developed cushioning materials maintained cushioning effectiveness under the investigated impact conditions.

Table 5: Summary of fracture test results by transportation impact condition

Drop height (m)	Number of tests	Number of fractures	Fracture rate (%)
1	15	0	0.0%
2	13	1	7.7%
3	12	0	0.0%

4.2.3. Interaction effects

Interaction effect analysis indicated that ceramic cup fracture was observed only once during the whole experimental study. Under Transportation Impact Condition 2 drop impacts, the fracture event in Sample 3 is determined to be 50:50 coconut and bamboo fibers. Based on the single fracture event observed, it is difficult to attribute product failure to any individual factor. The observed fracture may have been associated with a combination of material composition, thickness, and experimental variability. Reduced fiber bonding efficiency and decreased structural density could be caused by the proportion of homogeneous fibers, while the material thickness might limit the capacity of the cushioning material to withstand transportation impact conditions in the medium impact state. Thus, it can be deduced that an integrated consideration of several interactive parameters, like natural fiber composition, material thickness, and expected impact point conditions at transport time, should be key to the sustainable bio-based cushioning materials development. Hence, such integrated feasibility evaluation approaches can ensure effective performance when it comes to product protection as well as practical applications in product protection capability and logistics systems. Although clear factor effects could not be identified under the investigated conditions, the experimental data still revealed that the drop cushioning performance achieved was overall favorable across most investigated formulations. From a practical logistics packaging view, the preventive feature for product fracture in repeated drop impact scenarios is a significant engineering performance factor in sustainable cushioning (Jitkokkruad et al., 2023).

4.3. Validation results

The transportation impact response of drop impact tests is employed as the main response variable for the cushioning performance under the simulated transportation conditions in this study. The fracture-based evaluation technique is a practical and application-oriented way to study the capacity of developed bio-based cushioning materials for protection against effects caused by transport. While fracture or non-fracture measurements do not directly record continuous numerical information for cushioning mechanical properties, they have the utility of providing an engineering approximation for estimating the protection performance of transport against simulated logistics conditions in a preliminary scenario for a feasibility study. However, the binary way of transportation impact response (fracture or non-fracture) might have constrained the statistical sensitivity and variation of experimental data. Given that only one fracture occurred in the 40 experimental trials carried out, relatively small response variation was obtained, which may have hampered the statistical model from finding clear factor and interaction effects. The impact resistance behavior analysis provides useful preliminary insights into product protection capability, but additional quantitative response variables need to be included in future studies to gain a more thorough understanding of cushioning mechanics and materials. Potential response variables to consider include: impact acceleration, transmitted impact force, deformation displacement, compressive stress–strain behavior, quantitative cushioning performance evaluation, and energy absorption performance. In summary, the combination of instrument-based measurements in conjunction with advanced mechanical characterization techniques would enhance both the analytical robustness and preliminary engineering interpretation of the developed cushioning materials under practical transportation conditions. The material showed an acceptable absorption of impact during drop impact tests. Under the transportation conditions studied, the occurrence of product fracture was minimized, therefore suggesting practical effectiveness for protective packaging systems. The low occurrence of fractures observed in this experiment might also indicate the cushioning stability and product protection ability of the bio-based material developed under the logistics conditions being investigated. However, the response was binary, and the low variance in fracture-based responses weakened the sensitivity of the present statistical evaluation framework and

prevented the detection of clear factor effects and interaction effects. Finally, future studies should include a higher sample size, more extensive experimental settings, and continuous quantitative response variables (impact acceleration, deformation behavior, and energy absorption characteristics) for better statistical robustness and engineering interpretation of the results.

4.3.1. Data verification

The raw experimental data reported in Table 3 were checked, and all experimental trials were confirmed to have been conducted according to the established experimental framework. Here, we summarize the experimental details into the following: For Formulation 1 (70% coconut fiber: 30% bamboo residue, thickness 12 mm), nine experimental trials took place in three transportation impact conditions, performing three replications at each level. In Formulation 2 (30% coconut fiber: 70% bamboo residue, thickness 15 mm), we tested nine trials in the same drop impact situation. To evaluate Formulation 3 (50% coconut fiber: 50% bamboo residue, thickness 10 mm), four trials were carried out before termination of the experiment at Transportation Impact Condition 2, according to the set stopping condition for the study, at which point the experiment ceased after the observation of a fracture. Regarding Formulation 4 (100% coconut fiber, thickness 10 mm), nine control experiments were also performed. Similarly, nine experimental trials were finished for Formulation 5 (100% bamboo residue, thickness 10 mm). In total, 40 experimental trials were performed during the study, and full agreement with the data set displayed in Tables 4 and 5 was confirmed. The presented findings attest to the completeness of the experimental set-up and the absence of missing observations across the study.

4.3.2. Experimental validation

Validation of the cushioning material performance in this study was carried out at multiple levels to fully evaluate the laboratory performance, degree of agreement with existing knowledge, and its practical applicability. The main objective was to demonstrate that the experimental results could be successfully implemented in logistics and transportation systems as practical applications.

4.3.3. Performance validation

The highest performance of the cushioning, of Formulations 1 and 2, was achieved; therefore, no ceramic cup fracture was detected in any drop impact tests under the tested transportation conditions in the 40 experiments. Both formulations, therefore, reached 100% non-fracture rates, demonstrating excellent product protection ability and satisfactory cushioning performance. These results indicate that the generated bio-based cushioning materials can maintain stability and consistency under the simulated conditions of logistics handling. The results were consistent enough that experimental deviations lower than ±5% were deemed acceptable for practical engineering purposes. The consistent cushioning behavior found in the current study is evidence that the bio-based materials formulated here have shown acceptable reliability and repeatability for sustainable transport packaging applications. In addition, the structured experimental evaluation framework methodology offered a reliable basis for the successful identification of preferred material formulations, and with effective factor control based on statistical measurements, the validity of the experimental results was enhanced, as illustrated in Table 6.

Table 6: Validation results of bio-based cushioning material formulations

Formulation	Material composition	Thickness (mm)	Product protection rate (%)	Transportation impact response
1	Coconut husk 70%: Bamboo residue 30%	12	100%	Intact condition
2	Coconut husk 30%: Bamboo residue 70%	15	100%	Intact condition
3	Coconut husk 50%: Bamboo residue 50%	10	75%	Fracture observed
4	Coconut husk 100%	10	100%	Intact condition

The performance of each of the developed cushioning materials was compared to the existing literature in order to test the performance of the developed cushioning materials in comparison to other natural fiber-based cushioning materials. These were similar to those reported in previous literature, which were described by comparing the experimental measurements reported in the previous relevant literature. The bio-based cushioning materials created exhibited high product protection and impact resistance in transportation simulations. In this regard, natural fiber composites and bio-based packaging materials that have good impact protection, adequate cushioning performance, and structural stability are suitable for use as cushioning in agricultural biomass fibers. Consequently, the developed materials can be proposed as promising materials for practical applications, and their close matching with the current patterns of sustainable bio-based material development can be demonstrated.

4.3.4. Real transportation validation

Real transportation testing was carried out through the transportation of packaged products from Nakhon Nayok to Pathum Thani in order to confirm the practical usability of the prepared cushioning materials. Sample transportation conditions, comprising handling, stacking, road vibration, and impact forces induced by transportation, were represented by the selected

transport route. Experimental results suggested that no product damage was observed during the transportation trial, where the cushioning materials successfully maintained protective cushioning behavior under the investigated transportation conditions occurring under realistic operating conditions. These findings have also been validated for consistency with laboratory-scale experimental results; as such, they reinforce the practicality of the developed bio-based cushioning materials as packaging materials, particularly for logistics and transportation applications. In addition, the successful performance in real-world transportation demonstrated the potential use of these materials in green logistics and circular economy programs, as bio-based packaging alternatives are promoted to minimize petroleum-based cushioning materials.

On the approximately 110 km route from Nakhon Nayok Province to Pathum Thani Province, the transportation validation was conducted using a passenger pickup vehicle. The route included urban roads, rural roads, intersections, speed-control zones, and highway segments, representing typical transportation conditions encountered in regional logistics operations in Thailand. During transportation, the packaged ceramic products were subjected to routine handling, vehicle vibration, acceleration, deceleration, cornering, and normal loading–unloading operations. After completion of the transportation trial, all packaged products were visually inspected for fractures and packaging damage. No product fractures or visible damage were observed, confirming the practical protective capability of the developed bio-based cushioning materials under representative transportation conditions.

As a conclusion, the process of testing for experimental data, obtained results, and verification of experimental data were validated as shown in Table 7, and, as such, based on the overall verification, the accuracy, completeness, and reliability of the experimental data and results obtained were validated to prove the accuracy, completeness, and reliability of the experimental data and results obtained. The real operating conditions proved that the developed cushioning materials were practical. Therefore, the novel bio-based cushioning materials composed of bamboo residues and coconut husk fibers implied considerable potential as green replacements for conventional synthetic cushioning materials. In addition, the conclusions of this study also validated the deployment of green logistics and circular economy-oriented renewable packaging solutions.

Table 7: Summary of verification and validation results of the research process and experimental findings

Process	Verification item	Verification result	Status
Verification	Completeness of 40 experimental trials	All data fully completed	Intact condition
	Consistency between summarized results and raw data	Consistent across all formulations	
Validation	Structured experimental evaluation framework validation: Formulations 1 and 2	100% non-fracture rate achieved	
	Benchmark validation: Comparison with previous studies	Consistent with related literature	
	Operational validation: Real transportation test (Nakhon Nayok–Pathum Thani route)	No product damage observed	

5. Discussions

The bio-based cushioning materials were qualitatively compared with traditional petroleum-based cushioning materials, such as expanded polystyrene (EPS) foam and bubble wrap, to assess their capability for transportation protection (Table 8). Physical testing with comparable experimental conditions and direct mechanical comparisons was not possible for this work, but the bio-based cushioning materials displayed favorable properties during drop impact testing. The transportation impact testing appeared a fracture prevention rate of approximately 97.5%, by which the developed cushioning materials decrease product damage under the studied laboratory conditions. The observed cushioning behavior could be mainly due to the interaction between fiber composition, structural characteristics, and bonding quality in the formulated bio-based materials. The bamboo residue should provide rigidity, while the coconut husk fiber will most likely improve elasticity and enhance energy dissipation. The coupling relationship between these features can account for the robustness of transport protection shown in various formulations. However, due to the small number of fractures and the binary transportation impact response adopted in our current study, these interpretations are preliminary and need to be further validated via quantitative mechanical measurements.

Table 8: Qualitative comparison with conventional cushioning materials based on literature findings

Property	Developed bio-based material	EPS foam	Bubble wrap
Raw material source	Agricultural waste	Petroleum-based	Petroleum-based
Biodegradability	High	Very low	Very low
Fracture prevention efficiency	97.5%	High	Moderate
Environmental impact	Low	High	High
Renewable resource utilization	Yes	No	No
Sustainability compatibility	High	Low	Low

The developed bio-based cushioning materials suggested more effective transportation impact protection during drop impact testing compared with the packaging systems available without cushioning protection. The traditional EPS cushioning materials have excellent shock-absorbability (SA) capabilities, but they are petroleum-based, non-biodegradable, and present long-term environmental hazards. On the other hand, the cushion materials in this study were manufactured from renewable agricultural residues, including bamboo residues and coconut husk fibers, which supports sustainable packaging development, agricultural waste valorization, and Green Logistics application. Still, compared to benchmarking materials that are available in commercial form under standardized ASTM test conditions, quantitative measures should be performed to allow for objective comparison of performance in future investigations. While more quantitative comparisons are necessary, these results have shown that the derived bio-based cushioning materials exhibit good potential as sustainable protective transportation packaging materials.

The results provided in the present study confirm that the constructed bio-based cushioning materials exhibit not only engineering functionality but also potential for bio-based cushioning materials, along with the possible benefits to sustainable logistics systems and ecologically sound packaging (Pauer et al., 2019). The fabricated cushioning materials were derived from agricultural wastes; specifically, bamboo residues and coconut husk fibers from agricultural residue are used as cheap products produced with little added value, for example, from agricultural and community-based processing. The use of these renewable biomass resources promotes waste valorization strategies and minimizes the use of petroleum-based cushioning materials, such as expanded polystyrene (EPS) foam and synthetic plastic products in packaging systems (Cristofoli et al., 2023). The replacement of traditional plastic-based cushioning materials with biodegradable natural fiber materials can help minimize long-term plastic waste buildup within logistics and transportation systems from a sustainability viewpoint. Further, we know that the use of harvested biomass from renewable fields facilitates resource exchange and integrates with the circular economy framework, highlighting waste reduction, material recycling, and sustainable resource recycling (Khayyat et al., 2025). Results from experiments suggested that the fabricated cushioning materials were very compatible with green logistics applications (Seroka-Stolka and Ociepa-Kubicka, 2019). The elimination of eco-sensitive packaging waste and the encouragement of renewable materials may facilitate clean transportation and distribution activities. The suggested materials also show promise for low-carbon logistics systems with less reliance on fossil-resource-based packaging materials. From an environmental, social, and governance) point of view, the present study is mainly focused on the environmental sustainability dimensions concerning waste reduction, the use of renewable materials, and the development of environmentally responsible packaging. Value-added utilization of agricultural residues could provide the rural community with additional economic opportunities for transportation packaging, thus serving the local resource-based circular economy. While a life cycle assessment and carbon footprint analysis were not conducted and thus not suitable for the current research, the experimental observations generate preliminary evidence for the potential benefits of agricultural waste-based cushioning materials as sustainable alternatives to transportation packaging in green logistics and the circular economy. The bio-based cushioning materials have the potential to be practically applicable in sustainable transportation packaging, especially for SME and community-based production use. Since bamboo residues and coconut husk fibers are common agricultural waste products in many rural areas of Thailand, the developed materials will help local product utilization and decrease dependency on imported petroleum-based cushioning materials. The use of locally available agricultural waste materials has supply chain implications, which could result in a relatively short distance for material transport, lower packaging costs to procure, and support the supply chain efficiency of resource circulation in regional logistics networks (Ramingwong et al., 2019). Furthermore, through the conversion of agricultural residues into value-added cushioning materials, this could also promote the economic activity of agricultural communities and contribute to community-bound circular economy development activities. The developed cushioning materials also indicate a promising application as low-cost packaging substitutes for transportation and distribution processes involving packaging in transit, especially for goods with fragile nature and handling- and delivery-critical processes. Thus, they may provide guidance for the sustainable development of packaging and the practical implementation of green logistics in sustainable supply chain systems.

The focus of the proposed study was to examine the viability and protective capacity of bio-based materials fabricated from agro-waste for utilization in logistics. Therefore, it was intended as a preliminary engineering feasibility study rather than a comprehensive statistical assessment. A structured experimental evaluation framework was employed to systematically investigate material composition and material thickness-induced cushioning response when carrying out transportation impact simulations. The research primarily aimed at assessing the protective and impact resistance properties of the derived bio-based materials through drop impact testing and transportation impact response analysis. The experimental performance showed satisfactory protective ability and satisfactory cushioning performance behavior, confirming the possible use of the developed

material in sustainable transportation packaging systems. In terms of material characterization, this was not the main focus of the current study. Future studies should carry out further analysis of mechanical and physical properties, such as compressive stress–strain behavior, density, water absorption characteristics, tensile strength, and cushioning coefficient, to achieve greater insight into the structural and mechanical performance of these materials formed into the solution preparation. The results indicate that new characterization methods, such as SEM for monitoring fiber morphology and TGA or DSC for thermal stability studies, are recommended in future work in order to further investigate the interfacial bonding behavior, internal structural characteristics, and thermal properties of the bio-based cushioning materials (Ali et al., 2024). Moreover, testing for environmental biodegradability under controlled conditions and quantitatively testing the environmental sustainability performance of the developed material compared to conventional petroleum-based cushioning systems should be performed in future studies. The present study should be considered a preliminary phase on the sustainable cushioning feasibility, evaluating the drop impact condition performance and applicability of its packaging design in practice.

Its results serve as a basis for further development and characterization of bio-based cushioning materials in the context of green logistics and circular economy, as shown in Table 9.

Table 9: Recommended future material characterization analyses

Analysis type	Purpose
Compression stress–strain test	Evaluate structural rigidity and deformation behavior
Density measurement	Determine material compactness and internal structure
Water absorption test	Evaluate moisture resistance performance
Tensile strength test	Assess fiber bonding and mechanical strength
SEM morphology analysis	Observe fiber dispersion and interfacial bonding
TGA/DSC thermal analysis	Evaluate thermal stability characteristics
Biodegradation test	Assess environmental decomposition behavior

As indicated in Table 9, this research should be considered a preliminary engineering feasibility study on transportation impact performance and the practical use of bio-based cushioning materials for sustainable transportation packaging rather than material characterization research. The main objective of the study was to assess the capacity of agricultural waste-derived material for renewable cushioning for green logistics and the circular economy. Thus, extensive material characterization and high-level mechanical studies were beyond the scope of the present work and are suggested for any future work. Also, this study primarily addressed engineering feasibility and transportation protection performance. More thorough environmental metrics, such as Life Cycle Assessment (LCA), carbon footprint analysis, biodegradability evaluation, and end-of-life environmental impact assessment, were also beyond the scope of the present feasibility study. Implementing such assessments in further studies will allow for a comprehensive validation to evaluate the sustainability performance of bio-based cushioning materials. Instrument-based measurements, for instance, force sensors and accelerometers, are required to provide a quantitative characterization of cushioning mechanics and transportation impact performance in future studies.

6. Conclusion

The bio-based cushioning materials developed in this research consistent with product protection performance at a good level from simulated transportation impact conditions and sustainable transportation packaging applications, showing good prospects. The test results confirm the application of bamboo residues and coconut husk fibers as renewable cushioning materials in the context of green logistics and the circular economy. In 40 experiments, only one fracture event occurred, which implied a product protection rate of 97.5%, meaning that it was well-suited for transportation protection under the tested conditions. As a preliminary engineering feasibility study, the present study was mainly carried out. Complete material characterization, quantitative environmental assessment, and advanced mechanical measurements were therefore not under its purview. These directions are broad, and future research needs to further investigate them. First, the developed bio-based cushioning materials will be objectively compared with commercially available cushioning materials such as Expanded Polystyrene (EPS) foam and bubble wrap when subject to standardized ASTM tests to assess the ability of the materials to protect the user. Second, extensive engineering characterization methods, such as scanning electron microscopy (SEM), thermal characterization, compressive stress–strain analysis, impact acceleration measurement, deformation behavior, cushioning coefficient evaluation, and energy absorption analysis, will provide further detail on the material performance. Third, thorough environmental validation will be performed, including Life Cycle Assessment (LCA), carbon footprint analysis, biodegradability testing, and environmental impact assessment, to further verify the sustainability performance of the developed bio-based cushioning materials.

List of abbreviations

ASTM	American society for testing and materials
DOE	Design of experiments
DSC	Differential scanning calorimetry

EFS	Experimental feasibility study
EPS	Expanded polystyrene
LCA	Life cycle assessment
NaOH	Sodium hydroxide
PU	Polyurethane
RSM	Response surface methodology
SA	Shock absorbability
SEM	Scanning electron microscopy
SME	Small and medium-sized enterprise
TGA	Thermogravimetric analysis

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Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Aafrin BV, Babu PAS, Raj MD, and Sukumar M (2025). Testing of packaging materials. In: Sukumar M (Ed.), Food packaging technology: 159-187. 1st Edition, CRC Press, Boca Raton, USA. https://doi.org/10.1201/9781003668039-8

Adak B, Chatterjee U, and Joshi M (2025). Rubber-based sustainable textiles and potential industrial applications. Textiles, 5(2): 17. https://doi.org/10.3390/textiles5020017

Ahmed I, Lin H, Zou L, Li Z, Brody AL, Qazi IM, Lv L, Pavase TR, Khan MU, Khan S, and Sun L (2018). An overview of smart packaging technologies for monitoring safety and quality of meat and meat products. Packaging Technology and Science, 31(7): 449-471. https://doi.org/10.1002/pts.2380

Ali SAS, Ilankoon IMSK, Zhang L, and Tan J (2024). Packaging plastic waste from e-commerce sector: The Indian scenario and a multi-faceted cleaner production solution towards waste minimisation. Journal of Cleaner Production, 447: 141444. https://doi.org/10.1016/j.jclepro.2024.141444

Antony J (2003). Design of experiments for engineers and scientists. Butterworth-Heinemann, Oxford, UK.

Begum K and Islam MA (2013). Natural fiber as a substitute to synthetic fiber in polymer composites: A review. Research Journal of Engineering Sciences, 2(3): 46-53.

Cristofoli NL, Lima AR, Tchonkouang RD, Quintino AC, and Vieira MC (2023). Advances in the food packaging production from agri-food waste and by-products: Market trends for a sustainable development. Sustainability, 15(7): 6153. https://doi.org/10.3390/su15076153

Dill S, Brees K, Stahly A, Cheng E, Carpenter J, and Caplan L (2020). Mechanical shock during shipping of medications: The roles of packaging and transportation vendors. Journal of Pharmaceutical Sciences, 109(1): 670-676. https://doi.org/10.1016/j.xphs.2019.10.050 **PMid:31678248**

Elmessiry M, Badr AA, El-Tarfawy SY, Hassanin A, Elnahrawy A, and El Deeb RM (2025). Optimization of flax fabric/polyester composites for automotive interior applications: Mechanical performance, and moisture resistance. Egyptian Journal of Chemistry, 69(3): 687-708.

George DA, Lin BCA, and Chen Y (2015). A circular economy model of economic growth. Environmental Modelling & Software, 73: 60-63. https://doi.org/10.1016/j.envsoft.2015.06.014

Hao Y, Liu H, Chen H, Sha Y, Ji H, and Fan J (2019). What affect consumers' willingness to pay for green packaging? Evidence from China. Resources, Conservation and Recycling, 141: 21-29. https://doi.org/10.1016/j.resconrec.2018.10.001

Jayaprakash K, Osama A, Rajagopal R, Goyette B, and Karthikeyan OP (2022). Agriculture waste biomass repurposed into natural fibers: A circular bioeconomy perspective. Bioengineering, 9(7): 296. https://doi.org/10.3390/bioengineering9070296 **PMid:35877347 PMCid:PMC9311891**

Jitkokkruad K, Jarukumjorn K, Raksakulpiwat C, Chaiwong S, Rattanakaran J, and Trongsatitkul T (2023). Effects of bamboo leaf fiber content on cushion performance and biodegradability of natural rubber latex foam composites. Polymers, 15(3): 654. https://doi.org/10.3390/polym15030654 **PMid:36771955 PMCid:PMC9922013**

Jusakulvijit P, Bezama A, and Thrän D (2021). The availability and assessment of potential agricultural residues for the regional development of second-generation bioethanol in Thailand. Waste and Biomass Valorization, 12: 6091-6118. https://doi.org/10.1007/s12649-021-01424-y

Kassim N, Rahim SZA, Ibrahim WARAW, Shuaib NA, Rahim IA, Karim NA, Sandu AV, Pop M, Titu AM, Błoch K, and Nabiałek M (2023). Sustainable packaging design for molded expanded polystyrene cushion. Materials, 16(4): 1723. https://doi.org/10.3390/ma16041723 **PMid:36837353 PMCid:PMC9965373**

Khayyat MM, Jambi J, Kutbi N, Garout R, Al-Noumani L, Asiri R, and Balfaqih M (2025). Logistic caravan: A smart transportation system for green logistics and sustainable practices. International Journal of Advanced and Applied Sciences, 12(6): 154-168. https://doi.org/10.21833/ijaas.2025.06.015

Kittichotsatsawat Y, Jangkrajarng V, and Tippayawong KY (2021). Enhancing coffee supply chain towards sustainable growth with big data and modern agricultural technologies. Sustainability, 13(8): 4593. https://doi.org/10.3390/su13084593

Kittichotsatsawat Y, Rauch E, and Tippayawong KY (2024). Designing sustainability measurement of a Thai coffee supply chain using axiomatic design and business model canvas. Results in Engineering, 24: 103443. https://doi.org/10.1016/j.rineng.2024.103443

Kittichotsatsawat Y, Wattanutchariya W, Jongjareonrak A, and Seesuriyachan P (2025). Enhancing manufacturing operations within the supply chain for sustainable frozen shrimp production. Sustainability, 17(6): 2412. https://doi.org/10.3390/su17062412

Koinig G, Friedrich K, Rutrecht B, Oreski G, Barretta C, and Vollprecht D (2022). Influence of reflective materials, emitter intensity and foil thickness on the variability of near-infrared spectra of 2D plastic packaging materials. Waste Management, 144: 543-551. https://doi.org/10.1016/j.wasman.2021.12.019 **PMid:35379528**

Korhonen J, Honkasalo A, and Seppälä J (2018). Circular economy: The concept and its limitations. Ecological Economics, 143: 37-46. https://doi.org/10.1016/j.ecolecon.2017.06.041 **PMCid:PMC9566575**

Liu X (2024). Mushroom mycelium foam cushioning properties in protective packaging application. Journal of Applied Packaging Research, 16(1): 3.

Murugan A, Barik D, Faisal RS, Mani M, Dennison MS, Dinesh A, and Rajendran S (2025). Process parameter optimization for enhanced mechanical and thermal properties of kenaf/jute hybrid composites using grey fuzzy logic. Scientific Reports,

15: 36221.
https://doi.org/10.1038/s41598-025-20268-3
PMid:41102322 PMCid:PMC12533102

Nechita P and Năstac SM (2022). Overview on foam forming cellulose materials for cushioning packaging applications. Polymers, 14(10): 1963.
https://doi.org/10.3390/polym14101963
PMid:35631844 PMCid:PMC9143679

Pandey JK, Ahn SH, Lee CS, Mohanty AK, and Misra M (2010). Recent advances in the application of natural fiber based composites. Macromolecular Materials and Engineering, 295(11): 975-989.
https://doi.org/10.1002/mame.201000095

Parfenov A, Shamina L, Niu J, and Yadykin V (2021). Transformation of distribution logistics management in the digitalization of the economy. Journal of Open Innovation: Technology, Market, and Complexity, 7(1): 58.
https://doi.org/10.3390/joitmc7010058

Patel K, Acharya S, and Acharya GD (2024). Multi objective optimization of FDM parameters using Taguchi grey relation analysis for PLA specimen. Jurnal Kejuruteraan, 36(1): 113-122. https://doi.org/10.17576/jkukm-2024-36(1)-11

Pauer E, Wohner B, Heinrich V, and Tacker M (2019). Assessing the environmental sustainability of food packaging: An extended life cycle assessment including packaging-related food losses and waste and circularity assessment. Sustainability, 11(3): 925.
https://doi.org/10.3390/su11030925

Pickering KL and Le TM (2016). High performance aligned short natural fibre–Epoxy composites. Composites Part B: Engineering, 85: 123-129.
https://doi.org/10.1016/j.compositesb.2015.09.046

Pulikkalparambil H, Varghese SA, Chonhenchob V, Nampitch T, Jarupan L, and Harnkarnsujarit N (2023). Recent advances in natural fibre-based materials for food packaging applications. Polymers, 15(6): 1393.
https://doi.org/10.3390/polym15061393
PMid:36987173 PMCid:PMC10059869

Rajendran S, Al-Samydai A, Palani G, Trilaksana H, Sathish T, Giri J, Saravanan R, JoshuaRamesh Lalvani JI, and Nasri F (2025). Replacement of petroleum based products with plant-based materials, green and sustainable energy—A review. Engineering Reports, 7(4): e70108.
https://doi.org/10.1002/eng2.70108

Ralisnawati D, Kurniawan MP, Setioningrum D, and Astuti RP (2025). Development of a low-cost precision drop tester integrating digital height measurement and rapid release mechanism for academic packaging labs. Jurnal Ilmiah Inovasi, 25(3): 253-259.

Ramingwong S, Santiteerakul S, Tippayawong KY, Sopadang A, Limcharoen A, and Manopiniwes W (2019). Logistics performance of the Thai food industry. International Journal of Advanced and Applied Sciences, 6(5): 32-37.
https://doi.org/10.21833/ijaas.2019.05.006

Rashid S and Malik SH (2023). Transition from a linear to a circular economy. In: Bandh SA, Malla FA, and Hoang AT (Eds.), Renewable energy in circular economy: 1–20. Springer, Cham, Switzerland.
https://doi.org/10.1007/978-3-031-42220-1_1

Reichert CL, Bugnicourt E, Coltelli MB et al. (2020). Bio-based packaging: Materials, modifications, industrial applications and sustainability. Polymers, 12(7): 1558.
https://doi.org/10.3390/polym12071558 **PMid:32674366**

Seroka-Stolka O and Ociepa-Kubicka A (2019). Green logistics and circular economy. Transportation Research Procedia, 39: 471-479. https://doi.org/10.1016/j.trpro.2019.06.049

Shahdan D, Rosli NA, Chen RS, Ahmad S, and Gan S (2023). Strategies for strengthening toughened poly (lactic acid) blend via natural reinforcement with enhanced biodegradability: A review. International Journal of Biological Macromolecules, 251: 126214.
https://doi.org/10.1016/j.ijbiomac.2023.126214
PMid:37572810

Shojaei S, Shojaei S, Band SS, Farizhandi AAK, Ghoroqi M, and Mosavi A (2021). Application of Taguchi method and response surface methodology into the removal of malachite green and auramine-O by NaX nanozeolites. Scientific Reports, 11: 16054.
https://doi.org/10.1038/s41598-021-95649-5
PMid:34362984 PMCid:PMC8346513

Tomin M and Kmetty Á (2022). Polymer foams as advanced energy absorbing materials for sports applications—A review. Journal of Applied Polymer Science, 139(9): 51714.
https://doi.org/10.1002/app.51714

Yu RS and Singh S (2023). Microplastic pollution: Threats and impacts on global marine ecosystems. Sustainability, 15(17): 13252. https://doi.org/10.3390/su151713252

Zhang Z, Hao F, Hu D, Liu W, and Chen X (2025). Natural plant fiber-based materials for packaging applications–a review of recent innovations and developments. Advanced Materials Technologies, 10(7): 2401020.
https://doi.org/10.1002/admt.202401020