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Development of Sustainable Packaging Cushions from Coconut Waste Using 3D Printing Techniques

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ABSTRACT

Coconut fiber and coconut coir dust can be used to create environmentally friendly packaging. Additionally, recycled corrugated paper can be combined with tapioca starch to bind coconut coir dust and paper. Using these techniques, our objective was to develop a novel process for producing different items with coconut pulp paper and 3D-printed molds. The results indicated that the optimal weight ratios of paper, coconut fiber, and coconut coir dust for a bottle, corner cushion and wrapping cushions were 60:20:20, 60:20:20, and 80:20:0, respectively. The 3D-printed molds were designed with rounded chamfers to facilitate easy extraction of the molded paper. Both the bottle and corner cushions exhibited a tensile strength of 0.53 MPa with 12% NaOH treatment. The wrapping cushion demonstrated the highest flexural strength, at 10.33 MPa with 12% NaOH. Overall, NaOH treatment improved the mechanical properties of the coconut fiber compared to untreated fiber. For compression, the bottle and corner cushions achieved values of 3,196.38 N and 1,550.68 N, respectively. Furthermore, both the bottle and wrapping cushions passed the drop test from a height of 150 centimeters. In Thailand, the coconut industry reports revenues of approximately 4.66 billion THB in 2023 and produces 337 million metric tons of waste. This research demonstrates the great potential of coconut by-products, and the utilization of waste valued at 647 million THB. Future studies could explore innovative mold designs to enable the production of more complex packaging and decorative items, further enhancing the economic and environmental benefits of coconut waste utilization.

1. INTRODUCTION

The cultivation of aromatic coconuts in Thailand has steadily increased over the years. According to the Agricultural Production Information System, the cultivated area rose from 53,108 acres in 2011 to 81,376 acres in 2021. However, this increased production creates significant waste material, particularly coconut husk. This study focuses on waste reduction and value addition, utilizing aromatic coconut husks presents a significant opportunity (Thyavihalli Girijappa et al., 2019). Numerous research studies have explored various combinations of cushion materials. One notable finding was that a study combining coconut fiber with rice husk developed and tested a sustainable cushioning material. The optimal composition, found to be 50% coconut fiber with 50% rice husk, which showed superior performance in cushioning applications and exhibited optimal resilience, successfully enduring impacts up to a height of 92 centimeters in drop tests (Mohamad et al., 2024). However, this blend necessitates the use of latex adhesive, a chemical compound. Castro (2012) investigated the effectiveness of coconut fiber as a cushioning material through shock absorption tests. Interestingly, unprocessed coconut fiber wrappings performed better than coconut fiber wrappings that included binding agents. However, binders allow for denser packing of

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the cushioning material, reducing air gaps between the fibers and enhancing the flexibility of the material.

The study of the development of packaging paper from tender coconut husk with starch as an additive show that the paper has good mechanical properties and a degradation rate of approximately 70% within 20 days. This indicates that tender coconut husk is a biodegradable material with the potential to produce paper used for packaging materials (Pandiselvam et al., 2024). Another method for paper production involves blending 25% coir fiber with 75% newspaper and a 20-minute beating process to achieve optimal mechanical properties (Othman et al., 2013). A further investigation explored the combination of coir and cotton fiber as constituents to produce carry bags. The study yielded results indicating an Izod test impact value of 0.15 J, alongside a tensile strength measurement of 0.00268 MPa (Vishnu Nandan et al., 2023). In another investigation, waste paper and coconut fiber were combined in a 4:1 ratio, resulting in a tensile strength exceeding 0.00001 MPa. There is room for further exploration into the various types of waste paper and the optimal ratio of waste paper to coconut fiber in future investigations.

Currently, the pulp manufacturing process involves blending raw materials, molding pulp onto forms, extracting excess water, and pressing and drying it between two heated matched halves of a mold. However, this method demands significant heat energy and water consumption. Furthermore, the aluminum molds used in pulp molding machines are costly and require large quantities, this presents challenges for customization and affordability, especially within local communities. However, there is a promising alternative on the horizon. By utilizing recycled cardboard in conjunction with molds generated with 3D printers, a more cost-effective solution becomes accessible to local communities (Flowalistik, 2023). This straightforward approach not only simplifies implementation but also provides similar functionality. The aim of this study is to explore 3D printing technology's use in creating molds capable of shaping materials like coconut fiber, coconut coir dust, and recycled cardboard. The experiment seeks to determine the optimal ratios of these components, considering the functional efficacy of the 3D-printed molds in the molding process. The binder also serves as an organic material that promotes environmental friendliness. Integrating technology, innovation, and research can make these materials usable and applicable. The identified research gaps are: 1) The absence of a standardized formula for a coconut waste-based mixture in cushioning materials, and 2) Limited research in the application of 3D-printed molds for the production process of sustainable cushioning materials.

2. METHODOLOGY

The study investigated the composition ratios of materials used in shaping cushion-resistant materials for products (bottles) and packaging (corners) using the Triaxial Blend method. This method involves three types of materials: recycled corrugated paper, coconut fibers, and coconut coir dust. Since the wrapping shock-proof cushion requires flexibility when wrapping, coconut coir dust is not appropriate to be an ingredient.

Five different material ratios will be tested and adjusted accordingly to ensure suitability for each specific application (Table 1), with a focus on safety and efficiency of the produced cushion-resistant materials.

Table 1. Ratios of percentage formulation of materials

Ratio	Percentage Formulation			Remarks
	Corrugated paper	Coconut fiber	Coconut coir dust	
A	60	20	20	For bottle and corner cushion
B	40	20	40	Same as above
C	20	20	60	Same as above
D	80	20	0	For wrapping shock-proof cushion
F	60	40	0	Same as above

2.1 Material preparation

2.1.1 Coconut fiber

The preparation of coconut fibers can be divided into two steps. Step 1: Coconut fibers that have not been treated with chemicals are tested for mechanical properties, and the best fibers are selected for the next step. Step 2: Coconut fibers are treated with NaOH (Shoeb et al., 2024). In preparing chemically treated coconut fibers, the appropriate conditions for treating coconut fibers are studied. The main factor studied is the concentration of NaOH at three levels: 12%, 14%, and 16%, with a boiling time of 3 h at a temperature of 100±5 degrees Celsius (°C). In the chemical treatment process, NaOH concentrations of 12%, 14%, and 16% were selected to optimize the fiber's mechanical properties. These concentrations were chosen based on their effectiveness in breaking down lignin and hemicellulose, which improves the tensile and flexibility characteristics of coconut fibers. In various studies, around 12% NaOH is commonly used as it effectively removes lignin, hemicellulose, and other impurities from natural fibers. The % yield was calculated, revealing that 12% NaOH provided the highest % yield. Increasing the NaOH concentration resulted in a decrease in % yield (Sayakulu and Soloi, 2022). This concentration optimally improves fiber surface roughness, which enhances adhesion between the fiber and the matrix in composites, without over-degrading the fibers.

2.1.2 Coconut coir dust

To prepare coconut coir dust, it is initially passed through a standard mesh sieve with a size of No. 16 (gap size of 1.18 mm). This step aims to facilitate the subsequent use of coconut coir dust as a composite material for manufacturing impact-resistant materials. Then, the coconut coir dust that has undergone sieving is dried in a hot air oven at 60 °C for 24 h to maintain a constant moisture content of less than 10%.

2.1.3 Pulp paper

To shape impact-resistant materials, discarded cardboard is utilized. It is shredded into small pieces and soaked in water for 24 h to soften it, making it easier to pulp. Afterwards, it is finely pulped using a paper pulp beater.

2.1.4 Binder

Use a ratio of 20 g of tapioca starch to 200 mL of tap water per 100 g of material. Mix the starch and water thoroughly, bring to a boil, and stir until a sticky consistency is achieved. It should form a clear gel that looks like a wet paste glue.

2.1.5 Enhanced 3D printing mold process

The present study explores the use of 3D printing technology to create cushioning materials tailored for diverse packaging needs. Utilizing a Delta X 200 printer and 1.75 mm Poly Lactic Acid (PLA) filament, the mold design comprises male and female parts with a precise 1.5 mm gap to ensure optimal material thickness and flexibility. Key design considerations include the integration of multiple drainage holes to prevent air pockets to ensure uniform density. Additionally, the molds feature angled slopes in addition to rounded chamfers, approximately 3 mm radius, to facilitate the smooth removal of molded objects and avoiding any potential damage during the extraction process. The thickness of the cushioning material can be customized by altering the 1.5 mm gap, providing the necessary level of protection for different products. The 3D printing mold process was enhanced to support the specific needs of the coconut fiber composite material. Using PLA allows for a sustainable and flexible approach, aligning with the project's environmental goals and providing a cost-effective solution for mold modifications as required.

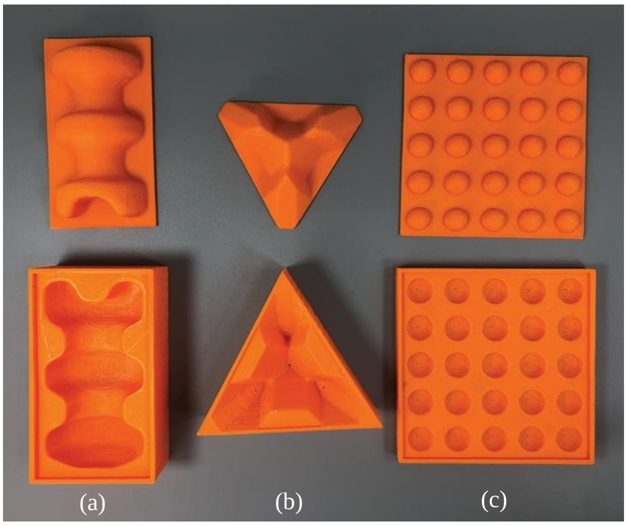

Figure 1. 3D-printed molds for (a) bottle cushion, (b) corner cushion, and (c) wrapping cushion

Three distinct usage patterns for the cushioning materials were tested:

1. Bottle cushion (Figure 1(a)): Molds were designed with cavities that conform to the contours of small glass bottles, such as perfume or herbal oil bottles, ensuring a secure fit and minimizing the risk of breakage.

2. Corner cushion for triangular packaging (Figure 1(b)): Molds produce triangular-shaped cushioning materials that fit into the corners of packaging, effectively reducing external impacts by absorbing and distributing force.

3. Wrapping cushion (Figure 1(c)): Molds create flexible, elongated cushioning materials suitable for wrapping or bundling products.

2.2 Mechanical properties of the samples

The samples will undergo mechanical testing according to ASTM standards using an Impact Testing Machine and a Universal Testing Machine (UTM) for impact resistance, tensile strength, flexural strength, and compressive strength. A) Impact Test: Rectangular specimens will be tested per ASTM D256 standards using the Izod method. B) Tensile Test: Dumbbell-shaped specimens will be tested per ASTM D638 standards for tensile and flexural strength. C) Compression Test: Compression testing will be conducted on bottle and corner configurations to determine compressive strength.

2.3 Scanning electron microscopy (SEM)

The microstructure of the board samples was analyzed using a Thermo Fisher Scientific Phenom ProX scanning electron microscope (SEM) with an acceleration voltage of 5 kV.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties

Table 2 presents the results of mechanical properties testing of five different formulations (labeled A to E) of cushion packaging. The formulations vary in the proportions of corrugated paper, coconut fiber, and coconut coir dust. The table shows the results of mechanical testing for cushion packaging formulations.

Table 2. Results of mechanical properties testing of cushion packaging (untreated).

Ratio	Formulation (%)			Impact		Tensile		Flexural		Compress	Remarks
	Corrugated paper	Coconut fiber	Coconut coir dust	Energy absorption (J)	Energy absorption per area (kJ/m^2)	Tensile strength (MPa)	Strain (%)	Max strength (N)	Max. stress (MPa)	Max. compression (N)	
A	60	20	20	0.19	0.60	0.47	1.62	11.22	6.43	1,105.59, 167.31	Bottle cushion, Corner cushion
B	40	20	40	0.11	0.33	0.14	0.62	9.43	4.07	1,020.86, 45.43	Same as above
C	20	20	60	0.28	0.86	0.13	0.59	10.70	2.00	1,033.58, 63.27	Same as above
D	80	20	0	0.05	0.15	0.36	1.96	9.38	8.68	-	Wrapping cushion
E	60	40	0	0.04	0.13	0.34	1.86	9.25	9.16	-	Same as above

3.1.1 Impact test

According to the Izod test principles, the test results indicate products (bottle cushion) and packaging (corner cushion), made from a mixture of paper, untreated coconut fiber, and coconut coir dust at ratio C, exhibits the highest ability to withstand impact or shock. This is evidenced by an absorbed energy of 0.28 J and an absorbed energy per unit area of 0.86 kJ/m². Following closely is ratio A, which shows absorbed energy values of 0.19 J and 0.60 kJ/m², respectively. Both sets of specimens exhibit ductile fractures, forming a 45° angle or flexural fracture, maintaining some degree of cohesion (Figure 2(b) and Figure 2(d)). In contrast, ratio B displays the least ability to withstand impact, with average absorbed energy values of 0.11 J and 0.33 kJ/m², respectively. The specimens exhibit brittle fractures, featuring a flat, smooth fracture surface, and separate upon impact (Figure 2(c)). The fracture characteristics significantly influence energy absorption during impact, with ductile fractures yielding higher impact energy absorption compared to brittle fractures. For impact-resistant material in wrapping form, those made from a mixture of paper and untreated coconut fibers at ratios D (Figure 2(e)) and E (Figure 2(f)), have the ability to withstand impact or shock that is relatively similar. The absorbed energy values are approximately 0.05 J and 0.04 J, respectively, with absorbed energy per unit area values around 0.15 kJ/m² and 0.13 kJ/m², respectively.

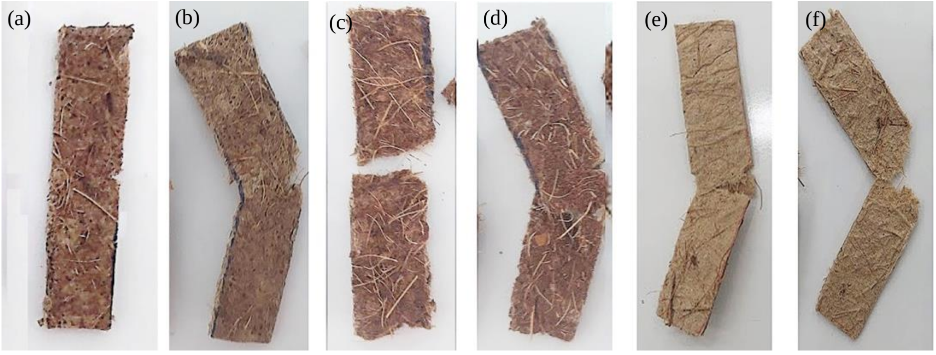

Figure 2. Impact test results of paper, untreated coconut fiber, and coconut coir dust at different ratios: (a) shape before testing, (b) 60:20:20, (c) 40:20:40, (d) 20:20:60, (e) 80:20:0, and (f) 60:40:0

3.1.2 Tensile test

The tensile test determines the stress when a material is subjected to force in a tensile manner, resisting separation (Figure 3). It was found that the ratio A of paper: untreated coconut fiber: coconut coir dust yielded the highest maximum tensile stress and strain values of 0.47 MPa and 1.62%, respectively, for impact-resistant products (bottle cushion) and packaging materials (corner cushion). Similarly, ratio B showed maximum tensile stress and strain values of 0.14 MPa and 0.62%, closely followed by ratio C with values of 0.13 MPa and 0.59%, respectively. An increase in the coconut coir dust content resulted in reduced maximum tensile stress and strain values due to its foam-like structure, which compromises adhesion and cohesion within the composite material. Enhancing tensile strength can be achieved by adding an appropriate amount of coconut coir dust, known for its natural fiber characteristics such as a porous structure and short fibers. However, excessive coconut coir dust may burden other composite materials without improving tensile strength, potentially due to poor interfacial bonding between particles and the matrix.

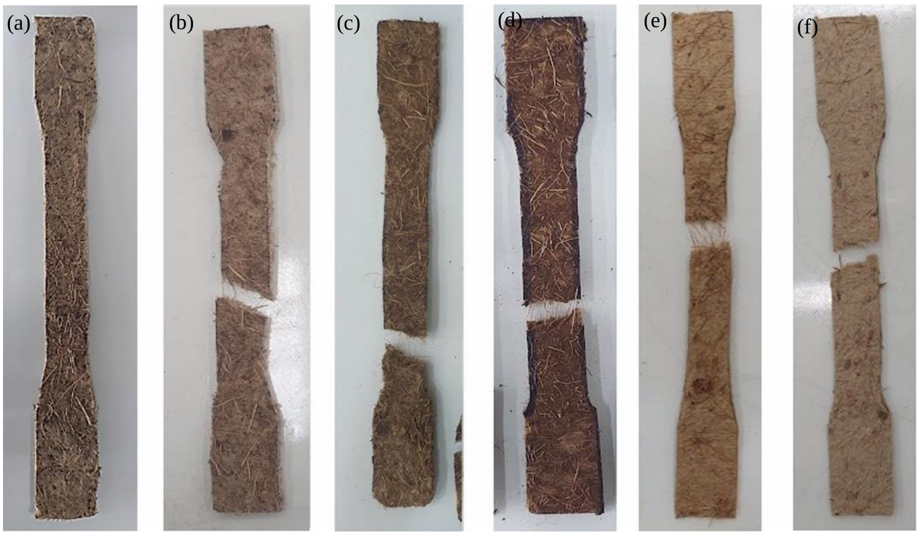

Figure 3. Tensile test results of paper, untreated coconut fiber, and coconut coir dust at various ratios: (a) shape before testing, (b) 60:20:20, (c) 40:20:40, (d) 20:20:60, (e) 80:20:0, and (f) 60:40:0\

3.1.3 Flexural test

In shaping impact-resistant products (bottle cushion) and packaging materials (corner cushion) from a mixture of paper (Figure 4), untreated coconut fiber, and coconut coir dust, ratio of 60:20:20 (Figure 4(b)) exhibits the highest flexural load and flexural strength, measuring 11.22 N and 6.43 MPa, respectively. Notably, ratio of 20:20:60 (Figure 4(d)) has a higher flexural load than ratio 40:20:40 (Figure 4(c)). However, under maximum force, both ratios of 40:20:40 and 20:20:60 exhibit flexural and fracturing characteristics. The strength of composite materials is notably affected by their thickness, with flexural strength decreasing as thickness increases. Ratios

80:20:0 (Figure 4(e)) and 60:40:0 (Figure 4(f)) exhibit similar flexural loads. The inclusion of both short and long coconut fibers in the wrapping-type cushioning material enhances its flexural resistance capabilities.

Figure 4. Flexural test results of paper, untreated coconut fiber, and coconut coir dust at various ratios: (a) shape before testing, (b) 60:20:20, (c) 40:20:40, (d) 20:20:60, (e) 80:20:0, and (f) 60:40:0

3.1.4 Compression test

When formed from a mixture of paper, untreated coconut fiber, and coconut coir dust at ratio A, bottle-type cushion packaging exhibits maximum compressive strength capabilities of 1,105.59 N, whereas corner-type cushion packaging reaches 167.31 N. Similarly, at ratio C, compressive strength capabilities are 1,033.58 N for bottle-type and 63.27 N for corner-type, while at ratio B, these values decrease to 1,020.86 N and 45.43 N, respectively. The fracture or tear characteristics of bottle-type and corner-type cushioning materials under compressive testing at a ratio of 60:20:20 (Figure 5(b)) show that the samples maintain their shape and incur less damage compared to ratios of 40:20:40 (Figure 5(c)) and 20:20:60 (Figure 5(d)). This is because the structure of corrugated paper consists of interconnected curved cells, which have a high compressive strength capacity. Similar to the bottle type, the 60:20:20 (Figure 5(f)) ratio can maintain its shape the best. Then, both the corner and bottle types with a 60:20:20 ratio were selected for testing after being treated with 12% NaOH.

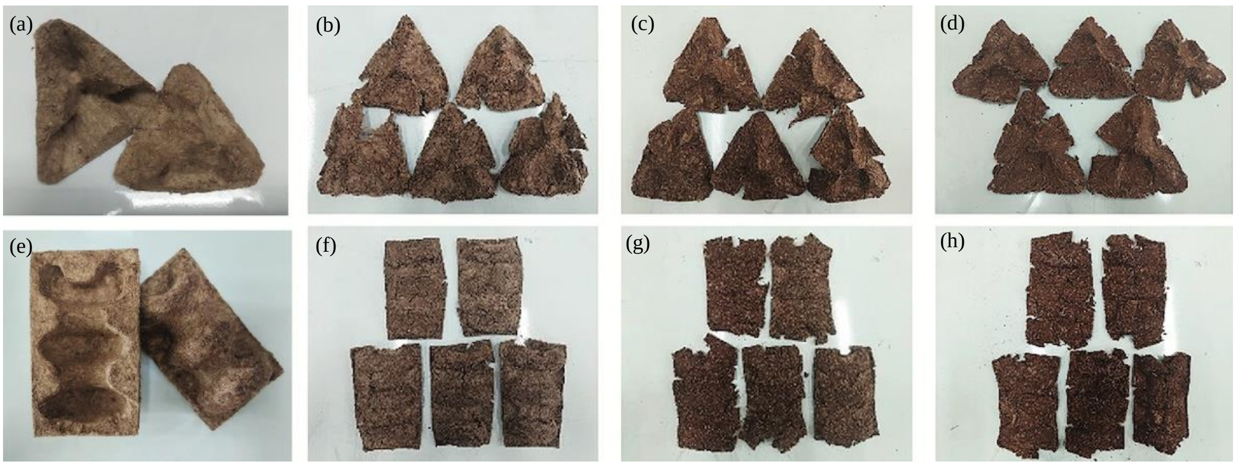

Figure 5. Compression test results of paper, untreated coconut fiber, and coconut coir dust at various ratios: (a) corner cushion shape before testing, (b) 60:20:20 for corner cushion, (c) 40:20:40 for corner cushion, (d) 20:20:60 for corner cushion, (e) bottle cushion shape before testing, (f) 60:20:20 for bottle cushion, (g) 40:20:40 for bottle cushion, and (h) 20:20:60 for bottle cushion

3.2 Coconut fiber treated with NaOH

It was found that cushion packaging products (bottles) and cushion packaging (corners) can be successfully produced using a mixture of paper, coconut fiber (12% NaOH treated), and coconut coir dust at ratio A (60:20:20) Additionally, cushioning material in wrapping form can be produced at ratio D (80:20:0) using the same coconut fiber treatment, which yielded the best mechanical properties compared to using untreated coconut fiber. Cushioning materials in wrapping type from the mixture of coconut fiber treated with NaOH demonstrate good flexibility - they can be rolled, folded, and bent effectively. NaOH exhibits superior mechanical characteristics compared to untreated coconut fibers (Table 3). NaOH accelerates breakdown and removes hemicellulose and lignin from cellulose. Lignin, a natural polymer binding cellulose fibers in plant cell walls and acts as a barrier against microbial degradation of cellulose and hemicellulose. Studies indicate that treated coconut fiber exhibits higher tensile strengths compared to untreated fiber (Mir et al., 2012). For instance, coconut fiber treated with 10% NaOH combined with ethylene vinyl alcohol copolymers (EVOH) and starch achieves tensile strengths ranging from 8.9 to 13.6 MPa (Rosa et al., 2009). In contrast, coconut fiber treated with 12% NaOH in cushioning material composite exhibits tensile strengths of 0.53 to 0.54 MPa. Additionally, the presence of coconut coir may affect the composite's overall hardness due to its soft and highly flexible nature (Mohan et al., 2025). Optimal force reception efficiency can be achieved by adjusting the amount of coconut coir dust. Bottle and corner cushions made by mixing paper, coconut coir dust, and coconut fiber treated with NaOH demonstrate compression strengths 2-3 times higher than cushions using untreated coconut fiber (3,196.38 N and 1,550.68 N for bottle and corner cushions, respectively).

Table 3. The mechanical properties testing results of bottle-type and corner-type cushion packaging, as well as wrapping-form cushioning materials, fabricated using a mixture of materials including coconut fiber treated with 12% NaOH.

Type	Formulation (%)			Impact		Tensile		Flexural		Compression
	Corrugated paper	Coconut fiber	Coconut coir dust	Energy absorption (J)	Energy absorption per area (kJ/m²)	Tensile strength (MPa)	Strain (%)	Max. flexural Strength (N)	Max. stress (MPa)	Max. compression (N)
Bottle cushion	60	20	20	0.25	0.79	0.53	1.64	11.59	4.54	3,196.38
Corner cushion	60	20	20	0.25	0.79	0.53	1.64	11.59	4.54	1,550.68
Wrapping cushion	80	20	0	0.08	0.25	0.54	2.52	10.33	10.15	-

3.3 Drop test

Three forms of final cushion packaging are used to protect bottles, boxes, and glass tubes (Figure 6). Impact resistance tests on cushioning materials commonly utilize the free-fall test method. In this test, glass bottles filled with water are placed into both bottle-type and wrapping-type cushioning materials. These packaged samples are then inserted into shipping boxes and dropped from specified heights - 30, 60, 90, 120, and 150 centimeters - repeatedly. Upon unpacking the boxes and inspecting the packaged goods, it was observed that the glass bottles did not crack or sustain any damage at any tested height level. This indicates that both bottle-type and wrapping-type cushioning materials made from coconut husk effectively resist impacts, thereby protecting the packaged goods from damage. This research utilizes only 20% coconut fiber in producing cushioning material. In contrast, cushioning materials specifically designed for glass bottles often require up to 50% coconut fiber mixed with rice husks to achieve optimal packaging performance (Mohamad et al., 2024).

3.4 Microstructure study

Scanning Electron Microscope (SEM) analysis was conducted to investigate the microstructure and potential failure characteristics of coconut fiber. This analysis included examining both the surface and cross-sectional features of fibers to assess how these characteristics could affect fiber-matrix adhesion and structural integrity under stress. Two different composition ratios were analyzed: 1) a mixture of paper, coconut fiber, and coconut coir dust at a 60:20:20 ratio, and 2) a mixture of paper and coconut fiber at an 80:20 ratio, with and without NaOH treatment.

The SEM images of untreated coconut fibers (Figure 7(a)) show a surface with both smooth and rough regions, resulting in an uneven texture that limits adhesion with the matrix, potentially leading to interfacial failure. The presence of lignin and fatty substances between cells provides a strong cohesion within untreated fibers. Embedded spherical structures, or tyloses, resemble small bubbles, which may contribute to structural failure points under stress. The cross-sectional SEM image (Figure 7(c)) reveals a honeycomb-like structure with numerous pores (lumens), which can enhance toughness and energy absorption (Hwang et al., 2016; Faria et al., 2023).

Upon NaOH treatment, the SEM images (Figure 7(d)) show expanded voids and increased surface roughness, which improve mechanical interlocking and fiber-matrix adhesion, reducing potential failure at the fiber-matrix interface. These morphological changes, including increased porosity, contribute to a stronger bond and mitigate interfacial failure, enhancing the overall structural integrity of the treated composite material.

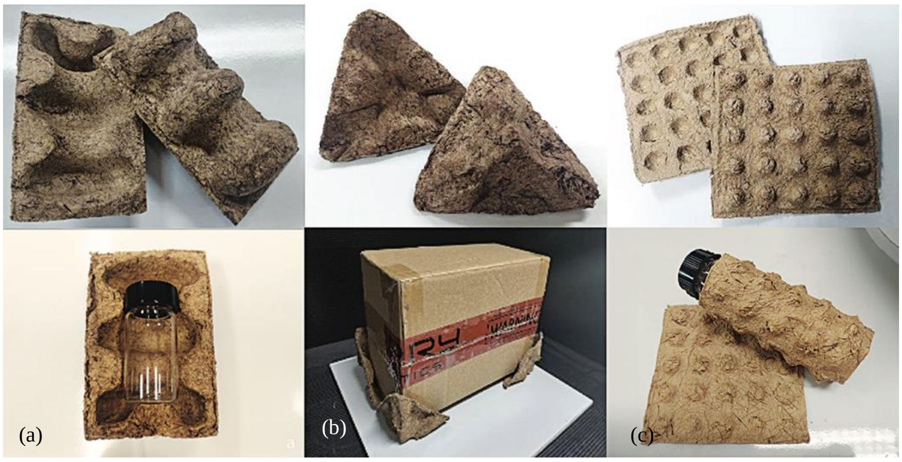

Figure 6. Three forms of final cushion packaging: (a) bottle type, (b) corner type, and (c) wrapping type

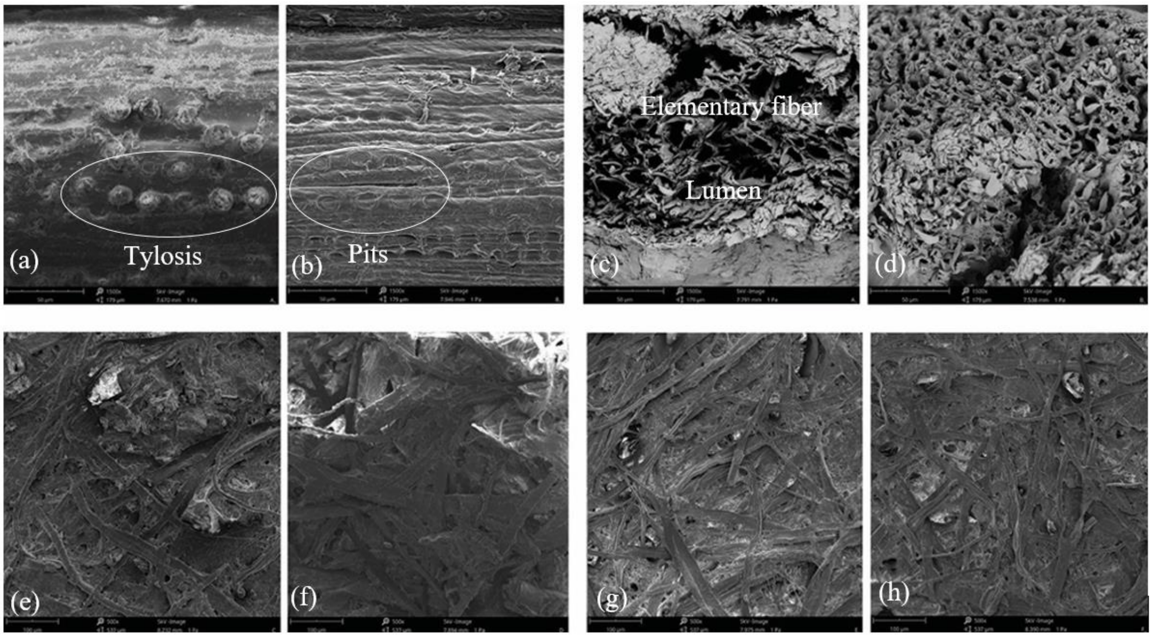

Figure 7. SEM micrographs of coconut fiber (a) Surface of fiber without NaOH, (b) Surface with 12% NaOH, (c) Cross section without NaOH, (d) Cross section with 12% NaOH, (e) Ratio of paper: coconut fiber: coconut coir dust at 60:20:20, (f) 60:20:20 with NaOH, (g) Ratio of paper: coconut fiber at 80:20 and (h) 80:20 with NaOH

This results in increased surface area and porosity for the fibers, leading to a significantly rougher and more uniform fiber surface (Rout et al., 2000; Tran et al., 2014; Bradley and Bradley, 2019). The enhanced porous structure of coconut fiber facilitates improved adhesion with other composite materials, thereby enhancing bonding and adhesion between materials. NaOH treatment also serves to cleanse the surface and unveil surface pores, referred to as pits (Figure 7(b)), which are absent on the surface of untreated fibers (Rosa et al., 2009). When untreated coconut fiber was used as a cushioning material alongside other components (paper and coconut coir dust), poor adhesion between the primary materials and the binder was observed. A non-uniform distribution and weak surface strength were evident, attributed to components within the fiber structure hindering adhesion between fibers and other materials (Figure 7(e) and Figure 7(g)). Studies show that even a slight increase in void content in coconut fiber reinforced composites can lead to significant reductions in tensile, flexural, and shear strengths between layers, up to 10-20% (Mehdikhani et al., 2019). In contrast, using NaOH-treated coconut fiber for cushioning materials results in strong adhesion between the primary materials and the binder (Figure 7(f) and Figure 7(h)). NaOH effectively removes lignin, hemicellulose, and other impurities from the fiber surface, breaking down fibers into smaller strands and promoting better integration and cohesion within the material. This process roughens the fiber surface, increases porosity, and creates larger voids, enhancing mechanical bonding between fibers and the matrix (Reddy and Yang, 2015). Improved compatibility between the primary material and binder contributes to enhanced mechanical properties, consistent with the findings of mechanical testing on cushioning materials described earlier.

4. CONCLUSION

This research confirms that the ratios of corrugated paper, coconut fiber, and coconut coir dust were 60:20:20 for bottles and corners cushions, and 80:20:0 for wrapping cushions. Using NaOH-treated coconut fiber enhances impact, tensile, flexural, and compression strengths, and the 3D printing process needs only two molds. Coconut coir dust provides rigidity, similar to box corners, while coconut fiber offers flexibility, making it ideal for shock absorption and flexibility in wrapping shock-proofing materials. This is the first study to use coconut coir dust in cushioning material, advancing the use of coconut-based materials.

NaOH treatment improves coconut fiber's fineness, porous structure, and blending capabilities. However, the chemical treatment may raise environmental and safety concerns. Future research could explore organic alternatives like amines and amino acids, which might offer eco-friendly options. The tensile strength of corrugated board ranges from 15 to 50 pounds per inch (0.10 to 0.34 MPa), and the bottle, corner, and wrapping cushions achieved values of 0.53 to 0.54 MPa, meeting or exceeding this requirement. Treated coconut fiber cushions offer better compression strength than untreated ones, ensuring adequate protection during transit.

Using 3D-printed molds simplifies the process, requiring only two molds instead of three. The material can be shaped with a manual press and Tapioca starch binding, avoiding the need for sun-drying or high temperatures. Molded fiber, with its potential for future development, could benefit from HP's advances in 3D printing and molded fiber technology (HP Development, 2024) and 3D-printed graphene-reinforced composites (Banupriya et al., 2024) Additionally, coconut husk's versatility allows for creative 3D applications in product designs like lamps, bins, and furniture. Future research should focus on large-scale 3D molds, diverse materials, and advanced polymers to enhance durability and functionality.

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REFERENCES

Banupriya R, Jeevan TP, Divya HV, Yashas Gowda TG, Manjunath GA. 3D-printed graphene-reinforced composites: Opportunities and challenges. Polymer Composit 2024; 46(2):1250-66.

Bradley W, Bradley S. Using coconut fiber and shell as functional fillers in polyolefin to enhance properties and reduce costs. SPE Sustainability Newsletter 2019;7:4-12.

D. Pinho da Costa Castro C, de Assis Fonseca Faria J, Dantas TBH. Testing the use of coconut fiber as a cushioning material for transport packaging. Materials Sciences and Applications 2012;3(3):151-6.

Faria DL, Mendes LM, Junior JBG. Effect of surface treatment on the technological properties of coconut fiber-reinforced plant polyurethane composites. Environmental Science and Pollution Research 2023;30(18):52124-40.

Flowalistik. Pulp it! - 3D printable recycled cardboard molds [Internet]. 2023 [cited 2024 Nov 8]. Available from: https://www.instructables.com/Pulp-It/.

HP Development. HP molded fiber for molded pulp production tooling [Internet]. 2024 [cited 2024 Nov 8]. Available from: https://www.hp.com/us-en/printers/3d-printers/molded-fiber-tooling.html.

Hwang C-L, Tran V-A, Hong J-W, Hsieh Y-C. Effects of short coconut fiber on the mechanical properties, plastic cracking behavior, and impact resistance of cementitious composites. Construction and Build Materials 2016;127:984-92.

Mehdikhani M, Gorbatikh L, Verpoest I, Lomov SV. Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance. Journal of Composite Materials 2019; 53(12):1579-669.

Mir SS, Hasan SMN, Hossain MJ, Hasan M. Chemical modification effect on the mechanical properties of coir fiber. Engineering Journal 2012;16(2):73-83.

Mohamad MAH, Onn N, Halim MAA, Yahya MS, Haidzir NAFM, Ibrahim MZ. Lean design of alternative packaging cushion material for glass bottles using rice husk and coconut fibre. Journal of Advanced Research in Applied Sciences and Engineering Technology 2024;33(2):107-19.

Mohan S, Thilagavathi G, Rajkhowa R. Composite panels utilizing microdust and coir pith for eco-friendly construction solutions. Journal of the Textile Institute 2025;116(2):175-82.

Othman MH, Main NM, Mon SZK, Mohamad Z. Development of paper using coir fibers as a packaging product. Asian Journal of Scientific Research 2013;6(2):207-16.

Pandiselvam R, Harikrishnan MP, Khanashyam AC, Basil M, Anirudh M, Manikantan MR, et al. Development and characterization of gelatinized starch doped microcellulose paper from tender coconut (*Cocos nucifera* L) husk. Process Safety and Environmental Protection 2024;184:615-23.

Reddy N, Yang Y. Natural cellulose fibers from corn stover. In: Innovative Biofibers from Renewable Resources. Berlin, Heidelberg: Springer; 2015. p. 5-8.

Rosa MF, Chiou B sen, Medeiros ES, Wood DF, Williams TG, Mattoso LHC, et al. Effect of fiber treatments on tensile and thermal properties of starch/ethylene vinyl alcohol copolymers/coir biocomposites. Bioresource Technology 2009;100(21):5196-202.

Rout J, Tripathy SS, Nayak SK, Misra M, Mohanty AK. Scanning electron microscopy study of chemically modified coir fibers. Journal of Applied Polymer Science 2000;79:1169-77.

Sayakulu NF, Soloi S. The effect of sodium hydroxide (NaOH) concentration on oil palm empty fruit bunch (OPEFB) cellulose yield. Journal of Physics: Conference Series. IOP Publishing 2022;2314(1):Article No. 12017.

Shoeb M, Kandasami RK, Singh S, Sebastian S. Framework for Treatment of coconut coir fibres through physico-chemical techniques. International Journal of Geosynthetics and Ground Engineering 2024;10(2):1-22.

Thyavihalli Girijappa YG, Mavinkere Rangappa S, Parameswaranpillai J, Siengchin S. Natural Fibers as Sustainable and Renewable Resource for Development of Eco-Friendly Composites: A Comprehensive Review. Frontier in Material 2019;6:Article No. 226.

Tran LQN, Minh TN, Fuentes CA, Chi TT, Van Vuure AW, Verpoest I. Investigation of microstructure and tensile properties of porous natural coir fibre for use in composite materials. Industrial Crops and Products 2014;65:437-45.

Vishnu Nandan H, Anish R, Jayaprasad G, Sunny S, Scaria Jomon J, Shibin R, et al. Experimental investigations on the mechanical properties and thermal analysis of coir-paper hybrid composite carry bag material. Materials Letters 2023;353:Article No. 132252.