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# Effect of Fibre Content and Surface Treatment on the Properties of Coconut Fibre/ Recycled Polypropylene (CF/rPP) Composites for FDM-Based 3D Printing

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ABSTRACT

*Growing environmental concerns surrounding synthetic fibres have accelerated the search for sustainable alternatives, with recycled polypropylene (rPP) emerging as a cost-effective thermoplastic for Fused Deposition Modelling (FDM) due to its favourable mechanical performance. Nevertheless, FDM-fabricated thermoplastic composites frequently exhibit brittleness, limiting their structural reliability, while the integration of coconut fibre with rPP remains underexplored. This study aims to develop coconut fibre/rPP composite filaments, evaluate their tensile and flexural properties, and examine their potential for sustainable additive manufacturing. Composites were prepared by blending coconut fibre with rPP via hot pressing, followed by filament extrusion and the 3D printing of Honeycomb Sandwich Structures (HCSS). Mechanical characterisation demonstrated that HCSS containing 1 wt% untreated coconut fibre achieved the highest performance, with tensile strength increasing by approximately 5.4% and flexural strength by 10.2% compared with treated coconut fibre. In contrast, fibre contents above 3 wt% resulted in reduced ductility, confirming an inverse relationship between fibre content and the material's ability to deform under tensile stress. Composites produced with treated fibres showed marginally improved properties; however, untreated fibres at low concentrations delivered competitive performance. These findings establish coconut fibre/rPP composites as a promising and environmentally responsible material system for FDM, with an optimal fibre content of 1 wt% balancing stiffness and ductility for enhanced mechanical reliability in 3D-printed structures.*

*Keywords: Fused deposition modelling, coconut fibre, honeycomb sandwich structure, recycle polypropylene*

## INTRODUCTION

The environmental burden associated with synthetic fibres has intensified the pursuit of sustainable alternatives in polymer-based manufacturing. While synthetic fibres deliver high mechanical performance, they contribute substantially to greenhouse gas emissions, energy-intensive production, and persistent end-of-life waste (Kumar & Shamprasad, 2021). As industries increasingly adopt circular economy strategies, the integration of bio-based reinforcements with recycled thermoplastics offers a promising route to reduce both environmental impact and manufacturing costs (Elfaleh et al., 2023).

Natural fibres such as jute, flax, and coconut exhibit low density, biodegradability, and significantly reduced carbon footprints compared with synthetic counterparts (Gonzalez et al., 2023& Ya et al., 2025). Among these, coconut fibre demonstrates comparatively high tensile strength and resilience, positioning it as a promising reinforcement for polymer composites (Ahmad et al., 2022). Simultaneously, recycled polypropylene (rPP) has emerged as a cost-effective and environmentally responsible thermoplastic with excellent recyclability and chemical resistance (Haque et al., 2010). Its thermal stability and potential for strong fibre–matrix interfacial bonding make it highly suitable for Fused Deposition Modelling (FDM), a widely used additive manufacturing process for functional prototypes and lightweight structural components (Ismail et al., 2022).

Despite significant advances in composite technology, most research on natural fibre–reinforced materials have concentrated on conventional processing methods such as injection and compression moulding (Pickering & Stoof, 2017; Arrigo et al., 2022). In contrast, the use of coconut fibre in fused deposition modelling (FDM) filament production and its application in fabricating load-bearing structures such as honeycomb sandwich structures (HCSS) remains limited. The HCSS configuration offers a unique advantage by combining a lightweight honeycomb core with stiff face sheets, resulting in a structure that achieves exceptional strength-to-weight and stiffness-to-weight ratios. This makes HCSS particularly significant for sustainable structural applications, where the use of natural fibre composites not only reduces reliance on petroleum-based systems but also enables the development of high-performance, lightweight materials for packaging, automotive, and construction sectors (Zhang et al., 2023)

The influence of fibre content, surface treatment, and dispersion on the mechanical performance, interfacial bonding, and ductility of 3D-printed composites has yet to be comprehensively examined. Nonetheless, recent investigations into natural fibre–based honeycomb sandwich structures (HCSS) have highlighted their promise as sustainable alternatives to conventional synthetic systems, with advances such as hemp-reinforced circular cores and flax fibre skins combined with foamed PLA cores (Haque et al., 2025). Coconut fibre, in particular, has received growing attention, demonstrating notable improvements in both mechanical and thermal performance (Zulkarnain et al., 2024a; Zulkarnain et al., 2024b). To date, most studies have employed FDM printing with PLA or PETG for core fabrication, while natural fibre composites are predominantly used as skins or reinforcements (Pino et al., 2024). A summary of these recent studies is provided in Table 1. However, comparatively few efforts have investigated polypropylene (PP) as a matrix material in 3D-printed HCSS. Overall, natural fibre reinforcements—including sisal, coconut, flax, and hemp have been shown to significantly enhance flexural strength and thermal insulation, underscoring their potential for developing lightweight and sustainable structural materials.

TABLE 1. Summary of these recent studies on natural fibre–reinforced honeycomb sandwich structures fabricated via 3D printing.

| Study | Natural Fibre Used | Core Material & Method | Key Findings |
|---|---|---|---|
| Pino et al. (2024) | Sisal (treated) | PLA & PETG cores via FDM | PETG cores stronger; PLA lighter; taller cores improve strength |
| Zulkarnain et al. – Thermal (2024) | Coconut, oil palm, sugarcane | 3D-printed core (material unspecified) | Coconut fibre provides superior thermal insulation |
| Zulkarnain et al. – Flexural (2024) | Coconut, oil palm, sugarcane | 3D-printed honeycomb core | Coconut fibre boosts flexural strength up to 100% |
| Hemp/Epoxy Haque et al. (2025) | Hemp | New circular honeycomb core | Good compressive/shear performance; eco-friendly alternative |
| Flax/PLA foam core Haque et al (2025) | Flax | Foamed PLA core via 3D printing | Sustainable alternative; bending properties compared to glass fibre |

This study addresses these gaps by developing coconut fibre/rPP composite filaments specifically designed for FDM and evaluating their tensile and flexural properties while investigating trade-offs between fibre content, stiffness, and ductility. The research further assesses the environmental and economic implications of such composites, offering insights into material behaviour, fibre–matrix interactions, and manufacturing feasibility. By establishing an optimal reinforcement approach, this study introduces a novel pathway for producing sustainable, high-performance filaments, contributing to the advancement of eco-friendly additive manufacturing technologies for structural applications.

## METHODOLOGY

The fabrication of a coconut fibre/recycled polypropylene (PP) (CF/rPP) composite sandwich structure encompass several essential phases: coconut fibre preparation, extrusion, fused deposition modelling (FDM) printing and mechanical testing. Each phase is crucial in ensuring the quality and performance of the final composite material. Figure 1 will depict the process flow for coconut fibre preparation, extrusion, FDM printing and testing undertaken in this study.

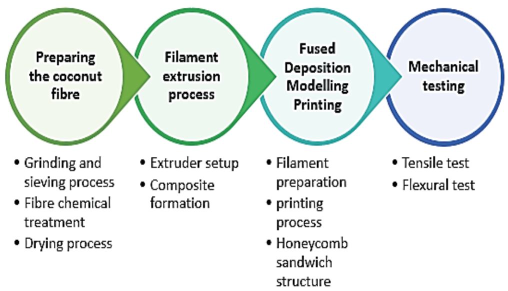



FIGURE 1. Process flow for the overall experimental approach in this study

## PREPARING COCONUT FIBRE

Coconut fibre, derived from unripe coconuts, is a natural fibre taken from the coconut husk. When they are immature, the subsequently become rigid and yellowed due to the deposition of a lignin layer on their walls. Coconut fibres exhibit significant stiffness and is utilised in items including floor mats, door mats, brushes, mattresses, coarse filler material and upholstery (Martinelli et al., 2023). In this study, the preparation of coconut fibre, which consists of 3 stages: grinding and sieving process, chemical treatment and the drying process.

The process commences with grinding the raw coconut husk into a fine powder. This powder is then sieved to achieve a particle size of less than 125 micrometres (µm) (Li et al., 2020). This step is crucial to ensure that the fibre particles are sufficiently small to be uniformly dispersed within the polypropylene matrix, which is essential for optimising the mechanical properties of the composite. Figure 2 illustrates the coconut fibre utilised in this study following the grinding process, along with the grinding equipment employed in this study.

(a) (b)

FIGURE 2. (a) Coconut fibre after the grinding process (b) grinder machine

After sieving, the coconut fibres are subjected to chemical treatment using a 6% sodium hydroxide (NaOH) solution prepared with distilled water (Figure 3(a)). As a strong alkaline agent, NaOH effectively removes lignin and hemicellulose from the fibres, thereby enhancing their surface characteristics and improving compatibility with the polypropylene matrix (Yew et al., 2019). Typical concentration reported in many studies is in the 2–10% NaOH range; 6% is a commonly used compromise that is effective while manageable in lab practice (Yew et al., 2019). This treatment is essential for promoting strong interfacial bonding between the coconut fibres and the polypropylene, which is critical to the overall mechanical strength and durability of the resulting composite material (Sabri et al., 2013).

Following the chemical treatment, the fibres are dried in an oven at 80 °C for 24 hours to eliminate residual moisture (Figure 3(b)). This drying step prevents potential issues such as mould growth and ensures consistent moisture content across the fibres. Both treated and untreated coconut fibres are then prepared for subsequent stages of the composite fabrication process.

(a) (b)

FIGURE 3. (a) NaOH solution for chemical treatment (b) Dried coconut fibre

## FILAMENT EXTRUSION PROCESS

During the extrusion process, chemically treated and untreated coconut fibres were compounded with recycled polypropylene (rPP) using a twin-screw extruder, with fibre contents of 1 wt%, 3 wt%, and 5 wt%. In this process, the polypropylene is gradually heated to its melting temperature generally between 160 °C and 180 °C, transforming it into a molten state. This enables the coconut fibres to be thoroughly incorporated into the polymer matrix through intense mixing and shear forces generated by the rotating screws. Achieving a uniform dispersion of the fibres within the molten polypropylene is essential for producing a consistent and mechanically stable composite material (Lee et al., 2023).

Subsequently, the homogeneous molten blend is forced through a specially designed die to form continuous strands (Figure 4). Throughout this process, key extrusion parameters including barrel temperature, screw speed, feed rate, and pressure are precisely controlled (Table 2). These parameters significantly influence fibre distribution, polymer-fibre interaction, and the overall rheological behaviour of the composite melt. Optimizing these conditions is crucial to ensuring that the final extrudate exhibits desirable properties such as improved mechanical strength, dimensional stability, and suitability for further processing, such as filament production for FDM 3D printing (Balasubramanian et al., 2025 and Fauzi et al., 2024). To assess the quality and consistency of the produced filaments, both physical appearance evaluation and microscopic surface analysis were conducted. These analyses aimed to investigate the external morphology, cross-sectional integrity, and internal structural characteristics of the filaments, providing insights into the influence of fibre content and chemical treatment on filament uniformity

FIGURE 4. Filament produced from the extrusion process

TABLE 2. Key Extrusion parameters

| Parameters | Value |
|---|---|
| Nozzle temperature | 190-220 °C |
| Barrel temperature | 180-220 °C |
| Screw speed | 300 rpm |
| Die diameter | 1.75 mm |
| Residence time | 2-4 minutes |
| Cooling method | Air |

## FUSED DEPOSITION MODELLING (FDM) PRINTING

The extruded composite material is subsequently processed into filament form, tailored for Fused Deposition Modelling (FDM) applications (Figure 5(a)). Maintaining a consistent filament diameter and uniform quality is critical to ensure accurate deposition and reliable printing performance.

During the FDM process, the composite filament is thermally melted and deposited in a layer-by-layer manner to build the intended geometry. The thermal and mechanical properties of the composite are particularly significant at this stage, as they directly affect the structural integrity, strength, and durability of the printed component.

In this study, Fused Deposition Modelling (FDM) was employed to fabricate a Honeycomb Sandwich Structure (HCSS), which is recognized for its lightweight characteristics and superior strength-to-weight ratio (Figure 5(b)). The HCSS consists of a honeycomb core configuration sandwiched between two face sheets, all manufactured using the developed composite filament. The model for printing was designed in SolidWorks and exported as an STL file, which was subsequently processed using Ultimaker Cura for slicing and print parameter adjustments. Figure 6 (a) presents the SolidWorks drawing of the specimen, while Figure 6 (b) illustrates the STL file as viewed in Ultimaker Cura.

The printing was performed using a Creality Ender 3 V2 printer (Figure 5(a)), in which the prepared filament was loaded into the extrusion system. Prior to printing, the hotbed and printer settings were calibrated to ensure dimensional accuracy and consistent deposition. The printing duration varied depending on the design complexity. This process was repeated for specimens prepared with different weight fractions of coconut fibre/ recycled polypropylene (CF/rPP). The corresponding FDM printing parameters and processing conditions are summarized in Table 3.

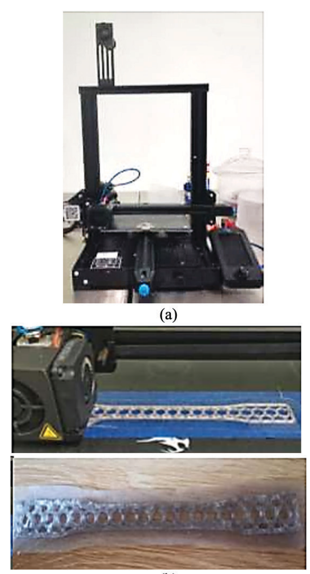
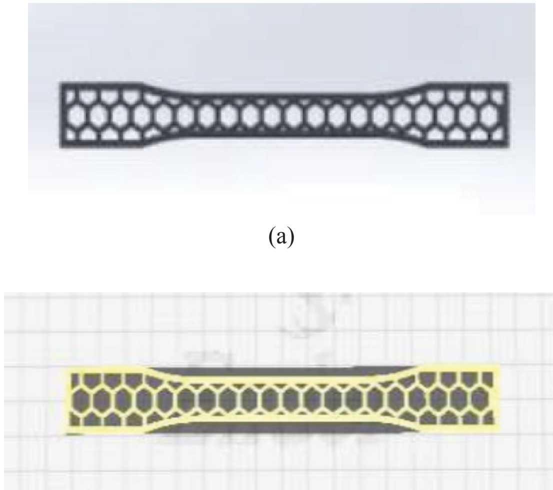



FIGURE 5. (a) FDM printing machine used in this study (b) Coconut fibre-reinforced recycled polypropylene (CF/rPP) composite Honeycomb structure (HCS) tensile strip sample



(a)

(b)

FIGURE 6. (a) SolidWorks drawing of the specimen (b) STL file as viewed in Ultimaker Cura

TABLE 3. 3D printing parameter

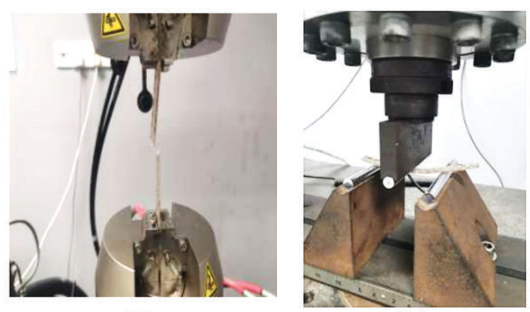
| Parameter | Details | Value |
|---|---|---|
| Nozzle | Diameter | 0.8 mm |
| | Temperature | 220-230 °C |
| Infill | Fill density | 100% |
| | Fill pattern | Brim |
| Printing | Speed | 30-40 mm/s |
| Temperature | Left extruder | 198 °C |
| | Platform | 98 °C |
| | Ambient condition | room temperature 25–27 °C |
| Cooling | Fan Speed | 2 |

## MECHANICAL TESTING

The fabricated composite HCS sandwich structures were subjected to mechanical testing to evaluate their tensile and flexural properties in accordance with established ASTM standards. Tensile testing was performed following ASTM D638, which specifies the method for determining the tensile properties of plastic and composite materials (Figure 7(a)). Tests were performed using a universal testing machine at a crosshead speed of 5 mm/min, as specified for Type I specimens. During the test, the specimens were mounted in a universal testing machine and loaded uniaxially until failure. This procedure enabled the determination of key parameters such as tensile strength, Young's modulus, and elongation at break. These properties provide critical insight into the material's ability to resist tensile deformation and its overall ductility which important factors for structural applications where in-plane stretching forces are encountered.

Flexural testing was carried out in accordance with ASTM D790, which outlines the procedure for measuring the flexural properties of unreinforced and reinforced plastics (Figure 7(b)). A three-point bending setup was employed at a crosshead speed of 2 mm/min, in which the specimen was supported at two ends and loaded at the midpoint until bending or fracture occurred. From this test, the flexural strength and flexural modulus were calculated. These values reflect the material's stiffness and its capacity to endure bending loads without permanent deformation or structural failure. For sandwich structures like the honeycomb core design, flexural performance is particularly significant, as it simulates out-of-plane stresses experienced in real-world loading conditions, such as those found in automotive panels, aerospace components, or structural floorings (Amir et al., 2021).

The combination of tensile and flexural testing provides a comprehensive mechanical profile of the developed composite sandwich structures, aiding in the evaluation of their suitability for load-bearing, lightweight applications (Kausar et al., 2023).



(a) (b)

FIGURE 7. (a) Tensile testing (b) Flexural testing

## RESULT & DISCUSSION

This chapter presents and discusses the findings obtained from the experimental investigation. The results are categorized into two main sections to provide a comprehensive understanding of the study's outcomes. The first section focuses on the characterization and visual observations of the developed coconut fibre/recycled polypropylene (CF/rPP) composite filament, which includes filament quality and morphology through Fused Deposition Modelling (FDM). These observations are essential in assessing the filament's suitability for 3D printing applications.

The second section covers the mechanical performance analysis of the printed specimens, including tensile and flexural testing. This analysis evaluates the structural integrity and mechanical behaviour of the printed components, offering insights into the material's performance under various loading conditions. The findings from both sections are critically analysed and compared with relevant literature to validate the outcomes and highlight the potential of CF/rPP composite filament in sustainable additive manufacturing.

## CF/RPP COMPOSITE FILAMENT PRODUCED

Figure 8 illustrates the physical appearance of the untreated and chemically treated CF/rPP filaments produced with three different coconut fibre weight percentages: 1 wt%, 3 wt%, and 5 wt%. Visually, all filament samples were successfully extruded with acceptable continuity; however, notable differences in filament surface quality and uniformity were observed based on the fibre content and treatment condition. At 1 wt%, both untreated and treated filaments demonstrated relatively smooth surfaces and good flexibility, indicating effective dispersion of coconut fibre within the recycled polypropylene matrix at low filler loading.

As the fibre content increased to 3 wt%, the untreated filament began to exhibit signs of surface roughness and slight inconsistencies in diameter, likely due to fibre agglomeration and weak interfacial bonding between hydrophilic fibres and the hydrophobic polymer matrix (Hasan et al., 2022). Conversely, the treated filament at 3 wt% showed improved homogeneity and surface texture, suggesting that the chemical treatment of fibres enhanced fibre–matrix adhesion and contributed to more stable extrusion. This improvement is attributed to the removal of surface impurities and the reduction of hydroxyl groups, which are known to negatively affect interfacial compatibility (Mohammed et al., 2022).

At the highest fibre content of 5 wt%, both untreated and treated filaments exhibited increased surface irregularities, and stiffness was inferred qualitatively based on filament handling during extrusion and 3D printing, where higher fibre content resulted in reduced flexibility and more brittle behaviour. However, the treated filament still maintained better structural integrity and was less prone to breaking during handling, compared to the untreated sample. This trend implies that while chemical treatment improves interfacial bonding and filament quality, higher fibre content introduces challenges such as increased viscosity during extrusion and reduced flowability, which can compromise filament quality if not optimized. Overall, these visual assessments support the significance of fibre treatment and optimal filler loading in ensuring filament printability for FDM applications.

| wt % | Untreated | Treated |
|---|---|---|
| 1 |  |  |
| 3 |  |  |
| 5 |  |  |

FIGURE 8. The untreated and treated filament produced for different wt % of coconut fibre

To further investigate the physical characteristics of the produced filaments, microscopic surface analysis was conducted on cross-sectioned samples following the approach of Yusuf et al. (2024). A digital microscope with 5× magnification was employed, and the samples were carefully sectioned with a sharp blade to expose the internal structure. The captured micrographs were then examined to evaluate the surface condition. Figure 9 displays the cross-sectional morphology of untreated and treated coconut fibre/recycled polypropylene (CF/rPP) composite filaments with three different fibre contents: 1 wt%, 3 wt%, and 5 wt%. The cross-sections provide visual insights into fibre dispersion, interfacial bonding, and overall filament uniformity. At 1 wt% fibre content, both untreated and treated filaments exhibit relatively smooth and homogeneous surfaces. The treated filament, however, shows fewer surface defects and a slightly more consolidated structure, indicating enhanced fibre–matrix interaction due to chemical treatment.

As the fibre content increases to 3 wt%, notable differences between untreated and treated filaments begin to emerge. The untreated filament displays signs of microvoids and irregularities, which are indicative of poor fibre dispersion and weak adhesion within the polymer matrix. In contrast, the treated filament at 3 wt% maintains a more compact and uniform cross-section, with fewer voids visible. This suggests that chemical treatment has improved fibre wettability and reduced the presence of interfacial gaps, resulting in better composite integrity during extrusion (Osman et al., 2025).

At 5 wt% fibre content, both filament types show increased heterogeneity in their cross-sections. The untreated filament appears significantly porous and fragmented, with large agglomerations of fibre and inconsistent internal structure. Meanwhile, the treated filament also experiences a decline in compactness but still retains better cohesion than the untreated sample. The observations imply that while chemical treatment can enhance filament quality, excessive fibre content may surpass the matrix's ability to encapsulate and bond with the fibres effectively, thereby compromising filament homogeneity and printability (Aida et al., 2021). These findings highlight the importance of optimizing both fibre treatment and content to ensure the structural quality of composite filaments for additive manufacturing applications.

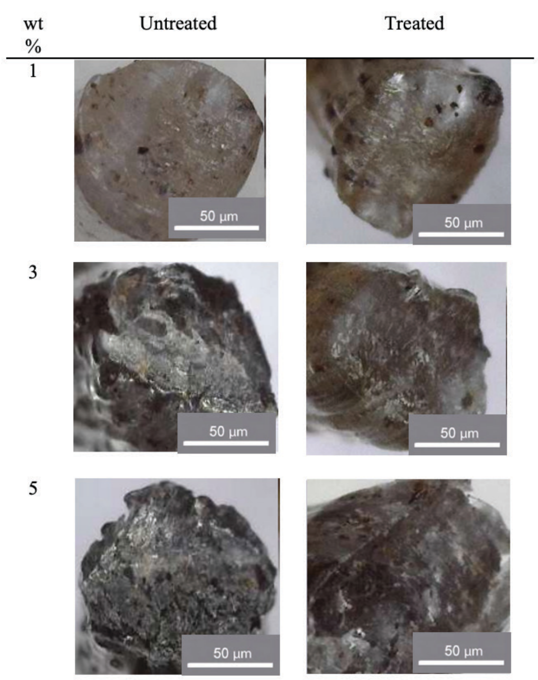



FIGURE 9. Cross-sectional images of untreated and treated filaments containing different weight percentages of coconut fibre were captured using a digital microscope at 5× magnification

## MECHANICAL PROPERTIES OF FABRICATED COMPOSITE HCS

Figure 10 presents the tensile strength (MPa) of honeycomb sandwich structures (HCS) fabricated using coconut fibre-reinforced recycled polypropylene (CF/rPP) filaments with varying fibre contents of 1 wt%, 3 wt%, and 5 wt%, comparing untreated and chemically treated fibres. A clear trend of decreasing tensile strength is observed with increasing fibre content for both untreated and treated filaments. The highest tensile strength was recorded at 1 wt% fibre content, where the untreated filament exhibited 6.537 MPa, slightly higher than the 6.202 MPa obtained for the treated counterpart.

At the lowest fibre content (1 wt%), the superior tensile performance may be attributed to improved stress transfer due to sufficient matrix encapsulation and limited fibre agglomeration (Plamadiala et al., 2025). The slightly higher tensile strength of the untreated filament at this level suggests that the untreated fibre retains its native flexibility and mechanical integrity, allowing more effective stress distribution within the matrix. However, with increased fibre content to 3 wt% and 5 wt%, a progressive reduction in tensile strength was evident. The untreated samples recorded tensile strengths of 4.898 MPa and 4.879 MPa, respectively, while the treated samples demonstrated further reductions to 4.583 MPa and 4.479 MPa.

This decline in tensile performance at higher fibre contents is likely a consequence of increased fibre agglomeration, impaired fibre dispersion, and reduced polymer matrix continuity, which collectively hinder efficient load transfer (Jiang et al., 2023). Although chemical treatment is typically intended to enhance fibre–matrix adhesion by reducing hydrophilicity, the treated samples underperformed at all fibre contents. This suggests the treatment process may have compromised fibre structure or induced brittleness, thereby reducing their reinforcing efficiency (Yew et al., 2019).

These findings highlight that optimal fibre content plays a critical role in achieving a balance between reinforcement and mechanical performance in CF/rPP composites. While 1 wt% fibre content shows the most promising tensile properties for FDM applications, the results also indicate a need for further refinement in surface treatment and dispersion techniques to maintain or improve mechanical performance at higher fibre concentrations.

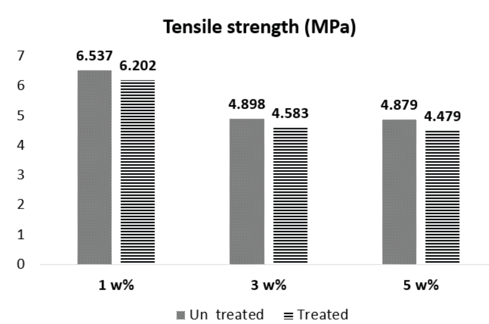



FIGURE 10. Tensile strength (MPa) of CF/rPP) composite HCS with varying fibre contents (1 wt%, 3 wt%, and 5 wt%). Each parameter study was conducted using three samples (n = 3).

Figure 11 illustrates the flexural strength (MPa) of CF/rPP composite HCS containing 1 wt%, 3 wt%, and 5 wt% coconut fibre, also compared under untreated and chemically treated conditions. A consistent trend of declining flexural strength is observed as fibre content increases, with untreated filaments consistently outperforming their treated counterparts at all loadings.

At 1 wt%, the untreated sample achieved the highest flexural strength of 2.161 MPa, while the treated sample recorded a slightly lower value of 1.961 MPa. This reduction may stem from the negative influence of chemical treatment on fibre–matrix bonding or potential degradation of fibre integrity, which can limit load-bearing capacity under flexural stress. At 3 wt%, both untreated and treated composite HCS experienced significant decreases in flexural strength, measured at 1.387 MPa and 1.123 MPa, respectively. This sharp decline may be attributed to inadequate fibre dispersion and the onset of microstructural defects that compromise mechanical response (Islam et al., 2024).

At 5 wt%, the untreated sample recorded 1.363 MPa, closely matching the value at 3 wt%, indicating a potential plateau in flexural performance degradation. However, the treated sample exhibited a more substantial reduction to 0.936 MP, the lowest value recorded in this study, suggesting that treatment-induced brittleness or poor interfacial compatibility becomes increasingly detrimental at higher fibre contents.

When compared with previous studies on natural fibre–reinforced honeycomb sandwich structures, distinct trends can be observed (Table 4). Pino et al. (2024) demonstrated that sisal fibre skins in a castor oil–based polyurethane matrix provided effective reinforcement, with PETG cores achieving 21–32% higher bending strength than PLA, although PLA cores offered a 13.8% weight reduction. In terms of thermal performance, Zulkarnain et al. (2024a) found that coconut fibre composites delivered the lowest thermal conductivity (~6.78 $W \cdot m^{-1} \cdot K^{-1}$), representing an 85.9% improvement compared to oil palm and sugarcane fibres. Further, their subsequent work, Zulkarnain et al. (2024b) reported that coconut fibre skins enhanced flexural strength by up to 100% and improved stiffness relative to unreinforced composites. Haque et al. (2025) introduced hemp/epoxy circular honeycomb cores, which achieved promising compressive and shear properties across densities of 0.144–0.276 g/cm³, while flax fibre–reinforced skins with foamed PLA cores demonstrated a sustainable alternative to glass fibre sandwiches, although quantitative bending values were not reported. In comparison, the present study advances the field by employing coconut fibre with a polypropylene (PP) core, a matrix material less explored in this context. Mechanical testing revealed that optimal performance was achieved at 1 wt% fibre content, yielding tensile strengths of 6.2–6.5 MPa and flexural strengths of 1.9–2.1 MPa. Unlike previous work using PLA or PETG cores, this study underscores the potential of recycled PP in producing cost-effective, mechanically viable, and industrially scalable honeycomb sandwich structures.

In conclusion, increased fibre content generally compromises both tensile and flexural properties in CF/rPP composites HCS, and chemical treatment under the investigated conditions did not yield improvements in mechanical performance. In fact, treated fibres consistently showed reduced strength compared to untreated ones. These findings underscore the importance of fibre content optimization and call for more effective treatment methods and processing strategies to enhance the mechanical properties of natural fibre-reinforced thermoplastic composites for FDM applications.

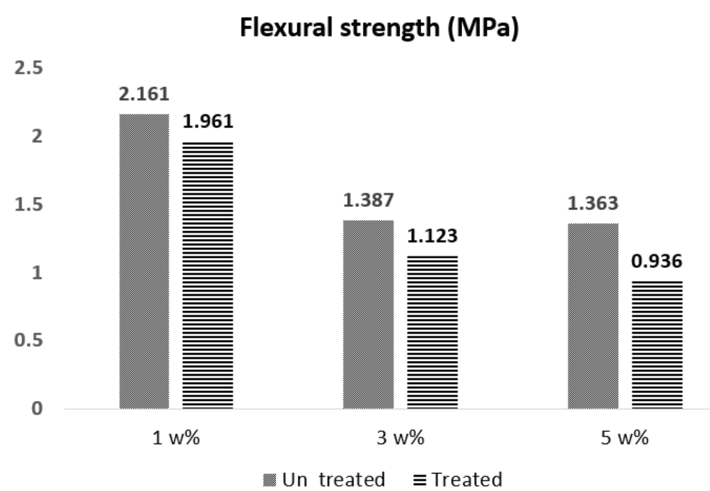



FIGURE 11. Flexural strength (MPa) of CF/rPP) composite HCS with varying fibre contents (1 wt%, 3 wt%, and 5 wt%). Each parameter study was conducted using three samples (n = 3).

TABLE 4. Comparison of recent studies on natural fibre–reinforced honeycomb sandwich structures with the present work.

| Study | Fibre Type / Skins | Core Material & Method | Key Mechanical/Thermal Findings |
|---|---|---|---|
| Pino et al., 2024 (Polymers) | Sisal fibre skins in castor oil–based PU (alkali-treated, 10 wt% NaOH, 4 h) | PLA and PETG honeycomb cores via FDM | PETG cores exhibited 21–32% higher bending strength than PLA; PLA cores were 13.8% lighter; increasing core height improved bending strength. |
| Zulkarnain et al., 2024 (Jurnal Teknologi) | Coconut, oil palm, and sugarcane fibre composite skins | 3D-printed honeycomb core (material not specified) | Coconut fibre composites showed lowest thermal conductivity (~6.78 $W \cdot m^{-1} \cdot K^{-1}$), an 85.9% improvement; palm oil and sugarcane fibres had higher conductivity (~10–11 $W \cdot m^{-1} \cdot K^{-1}$). |
| Zulkarnain et al., 2024 (Composites: Mechanics, Computations, Applications) | Coconut, oil palm, and sugarcane fibre composite skins (0–8 wt% loading) | 3D-printed honeycomb core | Coconut fibre skins increased flexural strength by up to 100% compared to unreinforced skins; improved stiffness and delayed failure. |
| Hemp/Epoxy, Haque et al. (2025) (JMEP) | Hemp fibre composite | Circular honeycomb core fabricated by continuous process | Compression and shear tests showed specific strength and stiffness suitable as eco-friendly alternatives to synthetic foams; performance varied with cell size (0.144–0.276 g/cm³). |
| Flax/PLA, Haque et al. (2025) (JCS) | Flax fibre–reinforced skins | 3D-printed foamed PLA core | Demonstrated sustainable alternative to glass fibre sandwiches; bending behaviour assessed but specific values not reported. |
| This study | Coconut fibre with fibre content of 1 wt%, 3 wt% and 5 wt% | 3D-printed honeycomb structure with PP core | Mechanical testing revealed that honeycomb sandwich structures achieved optimal performance at 1 wt% fibre content, with tensile strength reaching 6.2–6.5 MPa and flexural strength 1.9–2.1 MPa. Higher fibre contents led to agglomeration and reduced stress transfer. |

The results demonstrated that low fibre loading (1 wt%) promoted uniform dispersion, smooth surfaces, and reliable printability in both untreated and treated samples. Chemical treatment offered additional improvements in homogeneity at moderate loading (3 wt%), although its effectiveness diminished at higher fibre content. At 5 wt%, untreated and treated filaments both exhibited surface irregularities and structural inconsistencies, with more pronounced degradation in untreated samples. Mechanical testing of printed honeycomb sandwich structures revealed a consistent decline in tensile and flexural performance with increasing fibre content, with the best results observed at 1 wt% loading. Unexpectedly, untreated filaments generally outperformed treated ones, suggesting that the treatment process applied in this work may have caused fibre embrittlement or compromised interfacial bonding at higher concentrations

Overall, these outcomes highlight a key trade-off in natural fibre-reinforced composites: while fibre incorporation enhances sustainability and stiffness, excessive loading and suboptimal treatment conditions can reduce mechanical integrity and processability. Filaments with 1 wt% untreated fibre demonstrated the most favorable balance of print quality and mechanical performance, making them promising candidates for sustainable FDM applications. Future work should refine chemical treatment protocols, investigate compatibilizers to strengthen fibre–matrix adhesion, and explore advanced dispersion strategies to enable higher fibre contents without compromising filament or part performance.

## CONCLUSION

This study successfully developed and assessed coconut fibre-reinforced recycled polypropylene (CF/rPP) composite filaments for Fused Deposition Modelling (FDM), with a focus on the influence of fibre content and chemical treatment. Filaments containing 1 wt%, 3 wt%, and 5 wt% fibre were produced in both untreated and treated conditions, and systematically characterized through visual inspection, microstructural evaluation, and mechanical testing. The findings provide valuable insights into the interplay between processing, fibre–matrix interactions, and the resulting filament and part performance.

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## DECLARATION OF COMPETING INTEREST

None.

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