



## Analysis of the mechanical strength of composite materials reinforced with coconut fiber and recycled paper

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### Abstract

Waste materials that accumulate in the environment can cause serious ecological problems. Paper waste and coconut fibres are abundant materials, and improper management of these may lead to environmental degradation. Therefore, converting waste into value-added products represents an important sustainable approach. This study explores the development of a sustainable biocomposite material composed of recycled paper waste and coconut fibers as reinforcement phases, combined with a Polyvinyl Acetate (PVA) matrix system. The composite fabrication process involved several stages. Used paper was cut into small pieces, mixed with water at a 1:1 ratio, and blended to form a damp paper pulp slurry. Coconut fibres were combed, straightened, and cut into lengths of 1-9 cm, with weight fractions of 0-40%. The paper pulp was mixed with Polyvinyl Acetate (PVA) at a fixed weight fraction of 35%, followed by the addition of coconut fibres according to the designated compositions, and then molded in accordance with ASTM standards for tensile and bending tests. This study introduces a novel fully waste-based composite system combining used paper waste and coconut fibres with Polyvinyl Acetate (PVA) as a natural matrix, demonstrating effective mechanical reinforcement without synthetic resins or cement-based binders. The highest tensile stress (12.32 MPa) was obtained at a fibre length of 9 cm and a weight fraction of 20%, while the highest bending stress (72.6 MPa) occurred at a fibre length of 1 cm and a weight fraction of 10%. The tensile strength increased by 38% compared to the fibreless composite, confirming the reinforcing effectiveness of coconut fibres. These results highlight the potential of the developed composite as a sustainable alternative material for wood-based products in non-structural applications.

### Keywords:

Recycled paper, coconut fibre, eco-friendly composites, mechanical strength, SEM analysis

### 1 Introduction

Composite materials are created by combining two or more materials to achieve superior properties, such as light weight, and good mechanical characteristics. The use of synthetic fibers as composite reinforcements has rapidly expanded, with applications in industries such as automotive, marine, sports equipment, and even bulletproof vests. However, synthetic fiber waste poses a negative environmental impact due to its difficulty in naturally decomposing. As an environmentally friendly alternative material, natural fibers have been used as composite reinforcements, such as jute, pineapple,

ijuk, and coconut husk fibers. In Indonesia, coconut husks are a considerable waste that has not been fully utilized, even though they have high potential as reinforcement for environmentally friendly composites [1]. Several studies have reported the utilization of coconut fibre and paper-based composites for packaging applications, demonstrating sufficient mechanical strength while supporting the development of eco-friendly products. [2], and for various other applications, all of which supported the development of eco-friendly products [3]. Beyond packaging applications, various studies have demonstrated the effectiveness of agricultural and biomass waste materials as composite reinforcements. Coconut coir has been reported to exhibit considerable potential as a reinforcing material in homogeneous particle boards, showing performance comparable to that of wood particle-reinforced boards [4]. Similarly, bagasse fibres processed at specific mesh sizes and compression pressures have been shown to provide good mechanical strength and suitability for environmentally friendly board and construction material applications [5]. In addition, waste-based composites utilizing coconut shell, coir fibre, and recycled paper have been developed for functional products, including eco-friendly sound-absorbing panels [6] and paper substitute materials [7]. The mechanical behaviour of coconut fibre-reinforced composites has also been shown to depend strongly on fibre hybridization and matrix selection. Coconut coir fibres, combined with banana bunch fibres and banana stems, using a polyester resin matrix, achieved optimum strength when coconut coir was used as part of the reinforcement system [8]. Similarly, coconut coir fibres combined with wool using epoxy and araldite resin matrices resulted in maximum tensile strength, hardness, and toughness at specific fibre fractions [9]. These findings indicate that appropriate fibre combinations and matrix compatibility play a crucial role in determining composite performance, while also highlighting the potential of natural fibre-based composites as lightweight alternative engineering materials [10]. Further investigations have emphasized the influence of reinforcement characteristics and processing parameters on composite performance. Powder particle size has been reported to significantly affect mechanical properties, with a mesh size of 180 producing the highest impact toughness of 6422.78 J/m<sup>2</sup> [11]. Comparative studies on coconut shell-reinforced epoxy composites and coconut coir fibre-reinforced epoxy composites showed that shell-reinforced systems exhibited superior mechanical properties, while composites without coir fibre were more suitable for applications requiring high flexural strength [12]. Coconut coir has also been identified as a promising raw material for paper production, strengthening the potential integration of paper and coir in composite systems [13]. Moreover, coconut coir fibre has been reported to be highly effective in enhancing compressive and flexural strength, although tensile strength remains strongly dependent on fibre dispersion and matrix saturation [14]. Another study on coconut fibre-reinforced epoxy composites reported that optimum tensile and flexural strengths were achieved at a reinforcement volume fraction of 30%, as higher fibre content increased agglomeration levels [15]. In addition, epoxy matrix composites reinforced with alkali-treated coconut fibres showed improved tensile, flexural, and impact properties with increasing fibre length, while aligned fibre orientation positively influenced these properties [16]. Although extensive research on natural fibre-reinforced composites has been reported, most studies have primarily focused on synthetic or thermoset polymer matrices. In contrast, the combined utilisation of coconut fibre and recycled paper pulp within a water-based white wood glue (polyvinyl acetate (PVA)) matrix remains largely unexplored. While thermoset resins continue to dominate due to their high mechanical performance, their complex curing processes and limited recyclability highlight the need to investigate alternative matrices with simpler and more sustainable processing routes. To address this gap, the present study experimentally investigates recycled paper-coconut fibre composites using a PVA matrix, with particular emphasis on the influence of fibre length and fibre weight fraction on tensile and flexural performance. By systematically evaluating these parameters, this work aims to identify the optimal composition and

assess the feasibility of this fully waste-based composite as a sustainable material for non-structural engineering applications.

## 2 Research methods/ materials and methods

### 2.1 Composite production

The composite was fabricated using two reinforcing materials and one matrix with a total reinforcement-to-matrix weight ratio of 65%:35%. Used paper was first mixed with water at a 1:1 ratio and blended at 200 RPM to produce a homogeneous, moist, and cohesive paper pulp. Coconut fibres were then cut into lengths of 1, 3, 5, 7, and 9 cm. The reinforcement composition consisted of paper pulp and coconut fibre weight fractions of 100%:0%, 90%:10%, 80%:20%, 70%:30%, and 60%:40% based on the total reinforcement content. Subsequently, all components were mixed at 45 RPM for 10 minutes to ensure uniform dispersion prior to molding. The resulting mixture was poured into wooden molds without external pressure. Drying was carried out under direct sunlight for three consecutive days, for 6 hours per day (from 9:00 a.m. to 3:00 p.m.). It should be noted that this drying process may introduce uncontrolled variability and non-uniform moisture distribution across the specimens due to fluctuating environmental conditions, which is acknowledged as a limitation of this study.

### 2.2 Preparation of test specimens following ASTM standards

The dried composite material was shaped into tensile and bending test specimens, with five specimens prepared and tested for each compositional variation. The experimental data were analysed by calculating the mean and standard deviation to evaluate variability among specimens.

#### 2.2.1 Tensile test

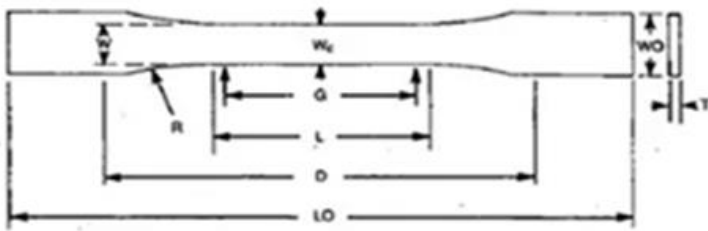


Fig. 1. Dimensions of the ASTM D638-03 tensile test specimen

Where:

- w = width of narrow section ( $13 \pm 0,5$  mm)
- L = length of narrow section ( $57 \pm 0,5$  mm)
- Lo = length overall (165 mm)
- G = gage length ( $50 \pm 0,25$  mm)
- wo = width overall ( $19 + 6,4$  mm)
- T = thickness (7 mm)

#### 2.2.2 Bending test

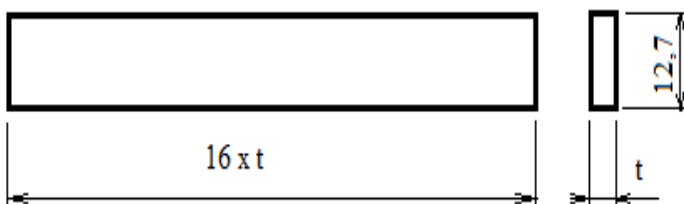


Fig. 2. Dimensions of the ASTM D790 bending test specimen

## 2.3 Calculation of strength

### 2.3.1 Tensile strength

$$\sigma_t = \frac{W}{A} \quad (1)$$

Where:

- $\sigma_t$  = Tensile stress (maximum or yield) (N/mm<sup>2</sup>)
- W = Load (maximum or yield) (N)
- A = Cross-sectional area (mm<sup>2</sup>)

### 2.3.2 Strain

$$\varepsilon = \frac{\Delta L}{L_o} \quad (2)$$

Where:

- $\varepsilon$  = strain (maximum or yield) (%)
- L<sub>o</sub> = Original length of the specimen (mm)
- $\Delta L$  = Change in length of the specimen ( $L_i - L_o$ ) (mm).

### 2.3.3 Modulus of elasticity

$$E = \frac{\sigma_t}{\varepsilon_t} \quad (3)$$

Where:

- $\sigma_t$  = Tensile strength (yield strength) (MPa)
- $\varepsilon_t$  = Tensile Strain (yield strain) (%)
- E = Modulus of Elasticity (MPa)

### 2.3.4 Bending strength (Modulus of rupture)

$$\sigma_b = \frac{3pl}{2bd^2} \quad (4)$$

Where:

- $\sigma_b$  = Bending strength (MPa)
- P = Load or force (N)
- L = Length of specimen (mm)
- b = Width of specimen (mm)
- d = Thickness of specimen (mm)

### 2.3.5 Bending strain

$$\varepsilon_b = \frac{6Dd}{L^2} \quad (5)$$

Where:

- $\varepsilon_b$  = Bending strain (%)
- D = Deflexion (mm)
- L = length of specimen (mm)
- d = thickness (mm)

### 2.3.6 Elastic modulus of bending

$$E_b = \frac{1}{4} \times \frac{L^3}{bd^3} \times \frac{P}{D} \quad (6)$$

Where:

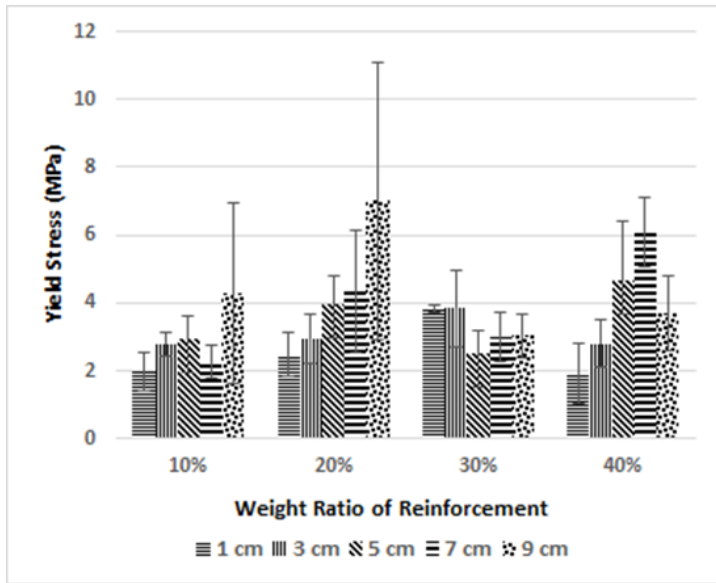
- E<sub>b</sub> = Elastic Modulus of bending (MPa)
- L = Length of specimen (mm)
- b = Width of specimen (mm)
- d = Thickness of specimen (mm)
- P = Load or force (N)
- D = Deflection (mm)

### 3 Result and discussion

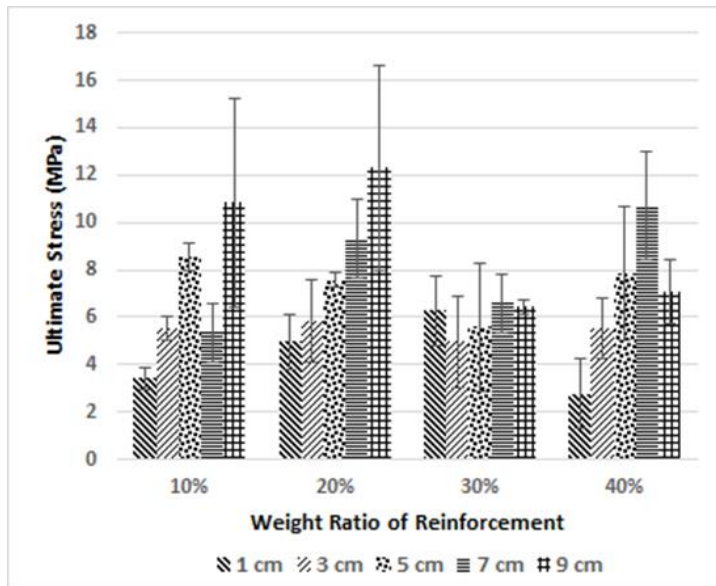
The reported values represent the mean of five specimens, with the standard deviation used to describe the degree of data variability.

#### 3.1 Tensile Tensile strength

The tensile test results for the fibre-free composite showed yield and maximum stresses of 1.89 MPa and 8.91 MPa, respectively, with yield and maximum strains of 0.08% and 1.17%.



**Fig. 3.** Yield tensile strength of recycled paper-coconut fiber composites at different fiber lengths (1-9 cm) and fiber weight fractions (10-40%), showing the highest strength at 9 cm fiber length and 20% reinforcement.



**Fig. 4.** Ultimate tensile strength of recycled paper-coconut fiber composites at different fiber lengths (1-9 cm) and fiber weight fractions (10-40%), presented with standard deviation error bars. The highest tensile strength was observed at a fiber of 9cm length and 20% reinforcement.

Fig. 3 and 4 illustrate that the composite's tensile strength increased with the fiber length, reaching its highest value of 12.32 MPa at a fiber length of 9 cm and a 20% weight fraction. This indicates that both fiber length and fiber content significantly influence the composite's tensile performance. At low fiber fractions (10-20%), the coconut fibers were well dispersed within the matrix, forming a strong interfacial bond that effectively transferred stress from the matrix to the fibers during loading. The improvement in

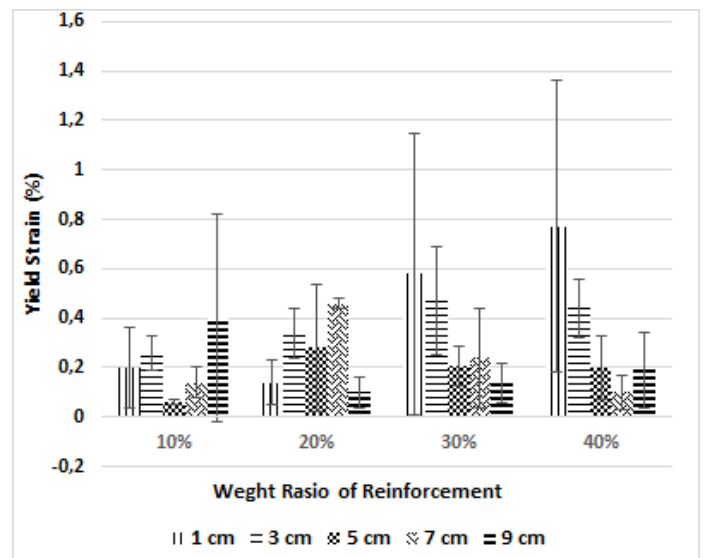
tensile strength was attributed to the formation of a continuous interface layer, which enabled better load transfer and reduced premature failure. However, at higher fiber fractions ( $\geq 30\%$ ), the tensile strength no longer increased consistently. This was due to the matrix's limited ability to fully wet and encapsulate the larger fiber surface area, leading to poor bonding, fiber agglomeration, and stress-concentration zones that initiated cracks more easily. This phenomenon, often referred to as matrix starvation, resulted in reduced tensile strength despite the increased reinforcement content.

The observed trend corresponds well with findings from previous studies. Increasing the fibre fraction in composite materials does not necessarily lead to a continuous improvement in mechanical performance. Beyond an optimal fibre content, excessive fibre clustering can occur, resulting in reduced efficiency of stress transfer between the matrix and the reinforcement [10,15]. Similarly, the mechanical strength of coconut fibre-reinforced composites increases with fibre length only up to a critical threshold, after which fibre entanglement and poor alignment contribute to a decline in tensile performance [17].

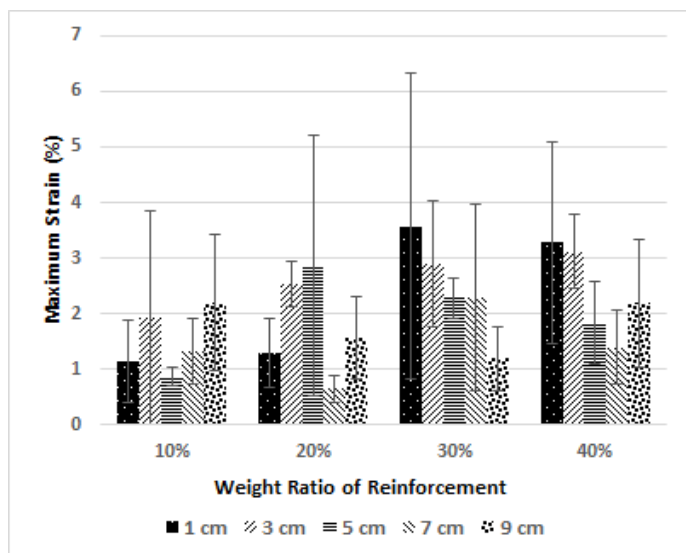
In this study, the highest tensile strength was obtained at 20% fiber fraction and 9 cm fiber length, indicating improved load transfer at this composition. The SEM micrograph shows (Fig. 13) fibres generally well embedded in the matrix with limited pull-out, supporting effective interfacial interaction. However, the presence of localized voids and uneven fibre distribution may explain the relatively large error bar, suggesting that although the average strength is superior, structural uniformity was not consistently achieved across all specimens. Beyond this condition, the matrix became insufficient to maintain proper adhesion. The SEM micrographs (Fig. 11 and 12) further confirm this, showing a smooth fiber-matrix bonding surface at the optimal condition, while excessive fiber fractions exhibited gaps and pull-out regions.

Overall, the results demonstrate that tensile strength in the paper-glue (PVA)-the interfacial adhesion quality and fiber length primarily governs coconut fiber composite. Stronger bonding promotes efficient stress transfer, while poor wetting and fiber agglomeration reduce performance. The 38% improvement over the unreinforced matrix indicates that coconut fibers can serve as effective reinforcements in environmentally friendly composites when properly proportioned and dispersed. These findings emphasize the importance of controlling fibre length and fraction to achieve optimum load transfer efficiency and interfacial bonding strength in natural-fibre-based composites.

#### Tensile strain



**Fig. 5.** Yield strain of recycled paper-coconut fiber composites at different fiber lengths (1-9 cm) and fiber weight fractions (10-40%), presented with standard deviation error bars.



**Fig. 6.** Effect of fiber length and fiber weight fraction on the ultimate strain of recycled paper-coconut fiber composites, including standard deviation to indicate experimental variability

Fig. 5 and 6 show the effect of fiber weight fraction and length on the tensile strain of the composites. The measured strain values were relatively small under both the yield and maximum conditions, indicating that the material exhibited a stiff, brittle response, particularly at low reinforcement fractions (10% and 20%). This behavior demonstrates that incorporating coconut fibers increased the composite's stiffness by restricting matrix deformation and enhancing load-bearing capacity.

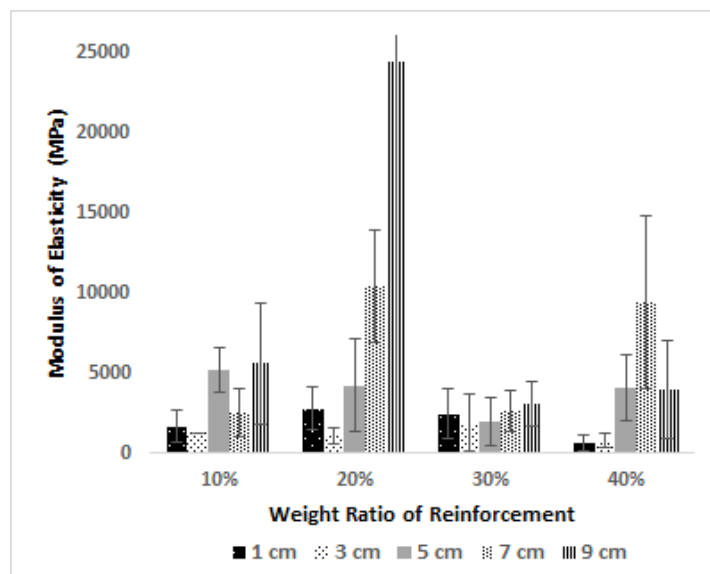
At higher fiber contents (30% and 40%), the strain values increased slightly. This was attributed to poor interfacial bonding between the fibers and matrix, leading to microslippage at the interface during loading. Inadequate bonding created localized deformation zones, leading to higher apparent strain without contributing to the real tensile strength. A similar phenomenon was observed by [19] and [20], who reported that excessive fiber addition often led to agglomeration, fiber entanglement, and uneven stress distribution, resulting in reduced strength but slightly increased strain due to localized fiber pull-out.

Fiber length also had a notable influence on strain behavior. Short fibers (1-3 cm) tended to be well distributed within the matrix, supporting limited deformation and preventing premature cracking. In contrast, longer fibers (5-9 cm) tended to bend or fold during mixing, leading to internal stress concentration and reduced strain capacity. This suggests that there exists a critical fiber length beyond which improved load transfer is offset by fiber misalignment and entanglement.

From the error bar analysis, several compositions exhibit relatively large standard deviations, such as 9 cm-10% (yield strain) and 1 cm-30% (maximum strain), indicating significant variability in deformation behavior. This suggests that fibre distribution, interfacial bonding consistency, and void formation were not uniformly achieved across all specimens. In contrast, smaller error bars at certain conditions (e.g., 5 cm-10% and 7 cm-20% for yield strain) reflect greater structural stability and more consistent stress transfer within the composite.

### Elasticity modulus

Fig. 7 presents the variation of the tensile modulus of elasticity with fiber content. The highest stiffness was recorded at a 20% fiber fraction, corresponding to the optimal tensile strength condition. At this level, the fiber-matrix interface was sufficiently developed, and the matrix volume was adequate to coat and bond the fibers effectively. Consequently, load transfer occurred efficiently, leading to higher modulus values. Beyond this fraction, the modulus decreased as matrix starvation occurred, and voids or interfacial gaps reduced the composite's overall rigidity.



**Fig. 7.** Tensile elastic modulus of recycled paper-coconut fiber composites at different fiber lengths (1-9 cm) and fiber weight fractions (10-40%), including standard deviation to indicate data variability.

These results indicate that the modulus of elasticity is strongly influenced by the balance between matrix continuity and fiber dispersion. A moderate fiber fraction promotes better adhesion and stiffness, whereas excessive reinforcement disrupts matrix continuity and diminishes stress-transfer efficiency. The trend observed aligns with the findings of [18], who noted that the stiffness of natural-fiber composites increases with fiber length and content only up to an optimum level, beyond which it declines due to poor stress distribution.

However, the error bar analysis reveals considerable variability in several compositions, particularly at 20%-9 cm (SD=26514.68) and 40%-7 cm (SD=5410.51), indicating substantial dispersion in stiffness values among specimens. This large deviation suggests that although the average modulus is high at the optimum condition, the internal structural uniformity and interfacial consistency were not fully achieved across all samples. In contrast, smaller standard deviations at certain compositions reflect more stable stress transfer and better structural homogeneity.

In summary, the tensile strain and elastic modulus results confirm that the optimum reinforcement condition (20% fiber fraction and 9 cm fiber length) produces a composite with the best balance between stiffness and deformability. The material under this condition exhibited strong interfacial adhesion, uniform fiber distribution, and efficient stress transfer, resulting in improved overall tensile performance.

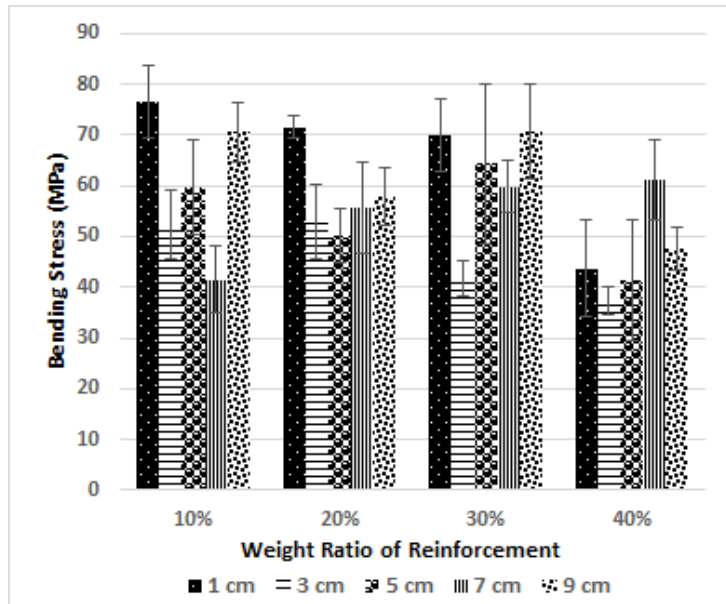
### 3.2 Bending

#### Bending strength

The results of the bending test for the fibre-free composite showed bending stress, bending strain, and bending modulus values of 47.1 MPa, 0.027%, and 114,829 MPa, respectively.

Fig. 8 illustrates the influence of fibre weight fraction and length on bending strength. The overall trend shows that as the reinforcement fraction increases, the bending strength tends to decrease. Similarly, increasing fibre length from 1 cm to 9 cm resulted in a gradual reduction in flexural strength. This behaviour is primarily due to differences in stress distribution during bending. Short fibres (1-3 cm) were more uniformly dispersed within the matrix and provided better stress transfer across the tensile and compressive regions of the specimen. In contrast, longer fibres (5-9 cm) were distributed less uniformly, often forming clusters or misaligned bundles that disrupted matrix continuity and acted as

stress concentrators. Such irregularities lead to premature cracking and reduced load-carrying capability under flexural loading.



**Fig. 8.** Effect of fiber length and fiber weight fraction on the flexural (bending) strength of recycled paper-coconut fiber composites, including standard deviation to indicate experimental variability.

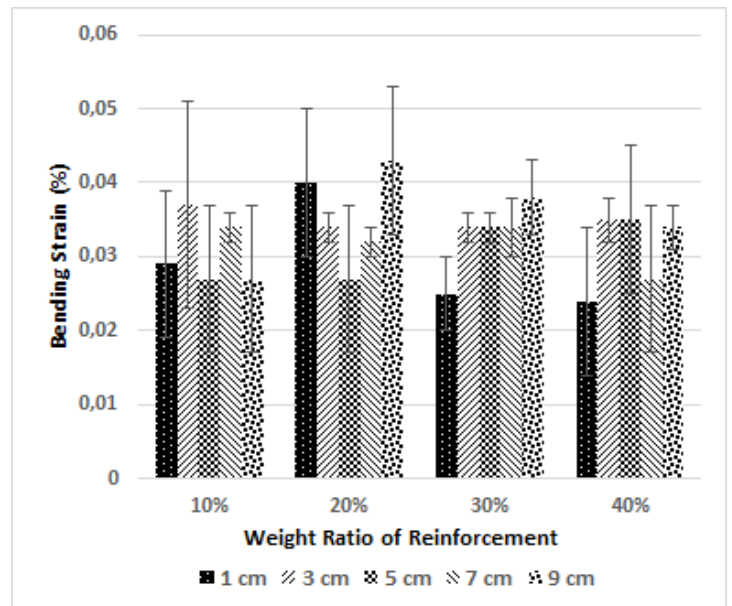
At higher fibre fractions ( $\geq 30\%$ ), the matrix's ability to encapsulate the fibres decreased significantly, resulting in the formation of voids and weak interfacial bonds. Consequently, load transfer efficiency diminished, and the composite became more susceptible to delamination or fibre pull-out under bending loads. Similar results were reported by [14] and [17], who observed that excessive fibre content can lower flexural strength due to inadequate matrix wetting and increased fibre clustering.

The error bar analysis indicates noticeable variability in several bending strength configurations. Relatively large standard deviations are observed at 30%-5 cm ( $SD=15.78$ ), 40%-5 cm ( $SD=11.79$ ), and 40%-1 cm ( $SD=9.45$ ), suggesting inconsistent flexural performance among specimens. This dispersion may be associated with non-uniform fibre dispersion, localized void formation, or uneven stress distribution during bending. In contrast, smaller standard deviations, such as 20%-1 cm ( $SD=2.19$ ) and 40%-3 cm ( $SD=2.69$ ), indicate greater structural stability and consistent load transfer under flexural loading. Overall, the larger error bars at higher fibre fractions and certain fibre lengths reflect reduced structural homogeneity, which contributes to variability in bending response.

### Bending strain

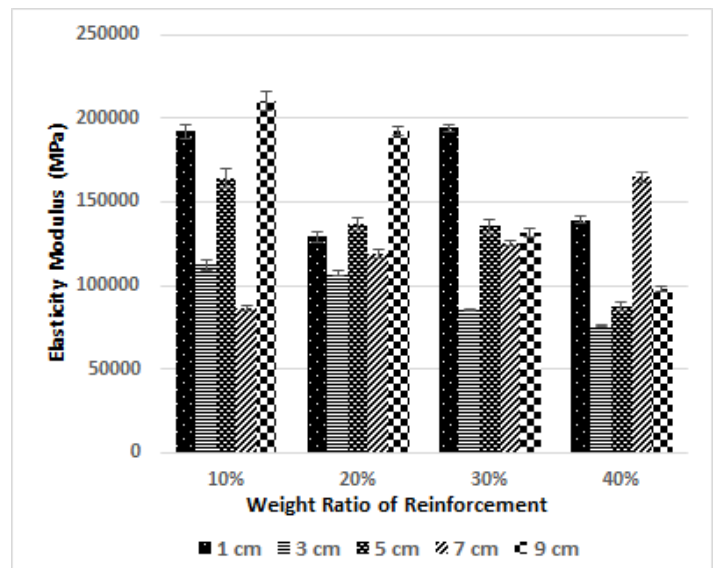
Fig. 9 shows that the bending strain generally increased with fibre length. This trend suggests that longer fibres contributed to greater energy absorption and flexibility before failure, even though the overall bending strength was lower. The increased strain can be attributed to micro-sliding and localized deformation along the fibre-matrix interface, which allowed the composite to bend further before breaking. However, this improvement in strain was insufficient to compensate for the loss in strength due to poor interfacial bonding at higher fiber fractions.

The error bar analysis shows relatively small standard deviations across most compositions, indicating consistent bending strain behavior among specimens. Lower SD values, such as 20%-3 cm and 30%-(3-5) cm ( $SD \approx 0.002$ ), reflect a stable deformation response and a uniform stress distribution during flexural loading. Slightly higher deviations were observed at 10%-3 cm and several 40% conditions ( $SD \approx 0.01-0.014$ ), suggesting minor variability, possibly due to local differences in fibre alignment or interfacial interaction. Overall, the small error bars indicate good reproducibility of bending strain performance.



**Fig. 9.** Flexural (Bending) strain of recycled paper-coconut fiber composites at different fiber lengths (1-9 cm) and fiber weight fractions (10-40%), presented with standard deviation error bars.

### Bending elasticity modulus



**Fig. 10.** Flexural (bending) modulus of recycled paper-coconut fiber composites at different fiber lengths (1-9 cm) and fiber weight fractions (10-40%), presented with standard deviation error bars.

The bending modulus of elasticity (Fig. 10) exhibited a pattern consistent with the flexural strength. The modulus decreased with increasing fibre content and fibre length. Composites reinforced with short fibres (1-3 cm) demonstrated higher stiffness due to better packing and more effective stress transfer. Longer fibres, on the other hand, reduced stiffness because of irregular orientation and reduced matrix continuity. As a result, the flexural modulus decreased, confirming that fibre length and distribution play a crucial role in determining the stiffness and rigidity of the composite.

The observed flexural behavior is consistent with the tensile test results, confirming that the overall mechanical performance of the composite is governed by the balance between matrix continuity, fiber dispersion, and interfacial adhesion. The optimal mechanical response, high tensile and adequate flexural strength, was achieved at a 20% fiber fraction and short to moderate fiber length. At these levels, the matrix sufficiently wets the fibers, enabling strong adhesion and efficient load transfer under both tensile and bending loads.

Overall, the bending test results demonstrate that while increasing fiber length enhances energy absorption capacity (strain), it reduces flexural strength and stiffness due to poor fiber alignment and interfacial integrity. Therefore, optimizing both fiber length and fraction is essential to achieve balanced tensile and flexural performance in natural fiber-based composites.

The error bar analysis shows moderate variability in bending modulus across compositions. Higher standard deviations at 10%-5 cm and 10%-9 cm indicate noticeable stiffness dispersion, likely due to differences in fibre orientation and matrix continuity. In contrast, lower SD values at 30%-3 cm and 40%-3 cm reflect more consistent flexural stiffness. Overall, the deviations remain proportionally small relative to the mean values, indicating generally stable and reproducible bending performance.

### Morphological SEM results

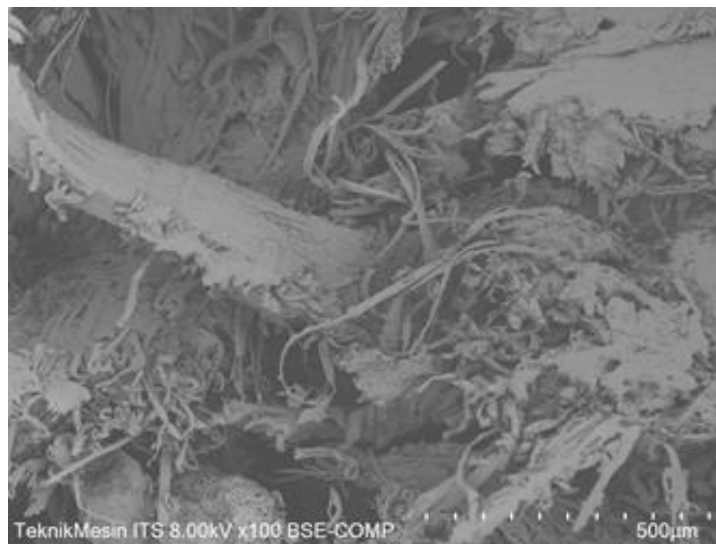
Morphological observations of the composite fracture surfaces were conducted using Scanning Electron Microscopy (SEM) better to understand the relationship between microstructural features and mechanical performance. Fig. 11 and 13 show the fibre-matrix interaction at two extreme conditions: the lowest tensile strength (fibre length 1 cm, 40% fibre fraction) and the highest tensile strength (fibre length 9 cm, 20% fibre fraction).



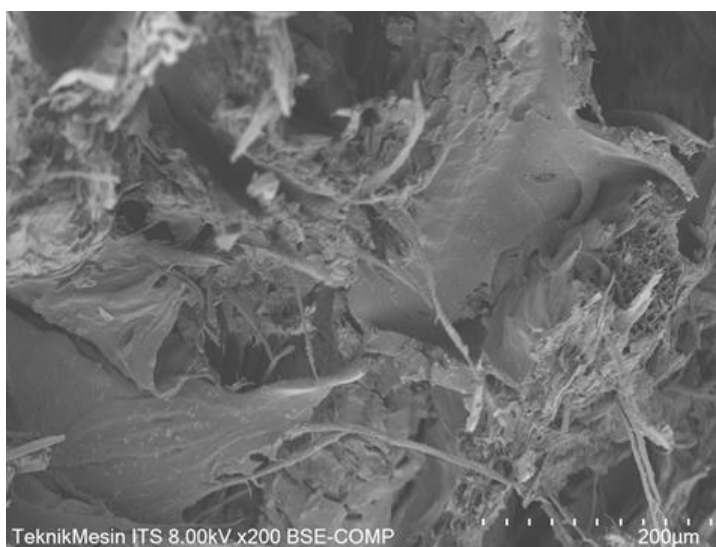
**Fig. 11.** Fibre condition on the fracture surface of the tensile test results (the lowest value). Fibre length 1 cm with a weight fraction of 40%. Magnification 30x

Fig. 11 presents the SEM image of the specimen that exhibited the lowest tensile strength. The surface shows several fibre pull-outs, voids, and poor matrix coverage, indicating weak interfacial adhesion between the coconut fibres and the polyvinyl acetate (PVA)-paper matrix. Insufficient wetting of the fibre surface resulted in incomplete bonding, leading to stress concentration and early fracture initiation under tensile loading. The high fibre fraction (40%) also reduced the available matrix, causing matrix starvation and further weakening the composite's internal structure. These morphological defects explain the observed reduction in tensile and bending strength at higher reinforcement contents.

Fig. 12 also shows weak fibre-matrix interfacial bonding, characterized by fibre pull-out, interfacial gaps, and incomplete matrix encapsulation. The coconut fibres appear unevenly distributed, whereas the recycled paper fibres do not form a compact reinforcing network, creating voids and stress concentration zones. These defects reduce interfacial shear transfer, promote premature debonding, and lead to failure dominated by pull-out rather than fibre fracture, ultimately resulting in low tensile strength.



**Fig. 12.** Fibre condition on the fracture surface of the tensile test results (the lowest value). Fibre length 1 cm with a weight fraction of 40%. Magnification 100x



**Fig. 13.** Fibre and interface condition on the fracture surface from the tensile test (the highest value). Fibre length: 9 cm, reinforcement weight fraction: 20%. Magnification: 500x

In contrast, Fig. 13 displays the SEM image corresponding to the highest tensile strength (fibre length 9 cm and 20% fibre fraction). The micrograph reveals a dense and continuous interface between the matrix and fibres, with minimal voids and clear evidence of strong fibre-matrix adhesion. The matrix appears to fully encapsulate the fibre surface, enabling efficient stress transfer during loading. The longer fibre length also promoted fibre interlocking and load bridging, which reduced the likelihood of pull-out and improved overall tensile strength. The presence of folded and aligned fibres contributed to enhanced load distribution across the composite, confirming the mechanical data trends observed earlier.

Fig. 14 shows that the specimen with the highest bending strength exhibits a dense and well-integrated microstructure, with coconut fibres firmly embedded in the matrix and minimal interfacial gaps, indicating strong interfacial adhesion. The recycled paper fibres form a compact reinforcing network that enhances mechanical interlocking and promotes uniform stress distribution. Improved matrix encapsulation and homogeneous fibre dispersion facilitate efficient interfacial shear transfer under bending load, delaying crack initiation and restricting crack propagation. This cohesive fibre-matrix interaction ultimately increases flexural load-bearing capacity, explaining the superior bending performance of this composite configuration.



**Fig. 14.** Fibre and interface condition on the fracture surface from the bending test (the highest value). Fibre length: 1 cm, reinforcement weight fraction: 10%. Magnification: 30x

The comparison between Fig. 11 and 13 clearly demonstrates that interfacial bonding quality is the key factor governing the mechanical behaviour of the composite. Strong interfacial adhesion enhances tensile strength and stiffness by promoting effective load transfer, while poor bonding and void formation result in early failure and reduced ductility. These findings are consistent with previous studies reporting that natural-fibre composites exhibit improved mechanical properties when good fibre–matrix adhesion is achieved [15,18].

The influence of fibre length and fibre fraction on mechanical performance is closely related to fibre distribution, void formation, and interfacial bonding quality. Excessive fibre length or content increases the risk of agglomeration, misalignment, and matrix starvation, leading to interfacial gaps and micro-voids that reduce stress transfer efficiency. In contrast, moderate fibre length and fraction promote uniform dispersion, adequate matrix encapsulation, and strong interfacial adhesion, thereby enhancing load transfer and overall composite performance.

Overall, the SEM analysis confirms that the mechanical performance of the paper-PVA-coconut fibre composite strongly depends on the microstructural uniformity and interfacial integrity. The optimum reinforcement condition (9 cm fibre length and 20% fibre fraction) produces a well-bonded interface with minimal defects, validating the macroscopic test results and highlighting the potential of this material as an environmentally friendly composite for structural applications.

#### 4 Conclusion

The experimental results confirm that fibre length and fibre weight fraction significantly influence the mechanical behaviour of the paper-PVA-coconut fibre composite. Tensile strength increased with fibre length up to an optimum condition (9 cm and 20% fibre fraction), beyond which excessive reinforcement reduced performance due to fibre agglomeration and insufficient matrix wetting. In contrast, flexural strength tended to decrease with increasing fibre length and content, as shorter fibres (1-3 cm) provided more uniform dispersion and improved stress distribution.

SEM observations supported these findings, revealing that higher mechanical performance was associated with dense interfacial bonding and minimal voids, whereas lower strength specimens exhibited fibre pull-out and poor adhesion. These results highlight the critical role of interfacial bonding quality in governing composite performance.

Overall, waste white paper and coconut fibre show potential as sustainable reinforcement materials when combined with polyvinyl acetate (PVA), particularly for applications requiring moderate mechanical performance. Further improvements should focus on controlled curing conditions, moulding pressure, and optimising fibre dispersion to enhance structural consistency and durability.

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