



COMPARATIVE MECHANICAL ANALYSIS OF FDM-PRINTED COPPER–NATURAL FIBER COMPOSITES

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Abstract: The development of sustainable materials for additive manufacturing has increased interest in combining metal-filled and natural-fiber-reinforced filaments. This study investigates the tensile, flexural, and impact properties of multi-material FDM composites based on Copper Filamet combined with FiberWood Brown and BDP Flax. The effects of material composition and printing parameters were evaluated experimentally. The results showed that composites containing 67% Copper Filamet achieved the highest mechanical performance for both material systems. Among all tested configurations, the Copper Filamet–BDP Flax hybrids exhibited the best overall properties, reaching a tensile strength of 25.45 MPa and an elastic modulus of 2623.50 MPa, while also outperforming the Copper Filamet–FiberWood Brown composites in flexural and impact tests. The BDP Flax reinforcement improved load transfer, stiffness, strength, and energy absorption capacity, despite the predominantly brittle behavior observed for all samples. Overall, the findings demonstrate that Copper Filamet–BDP Flax hybrid composites are promising materials for sustainable multi-material FDM applications requiring enhanced mechanical performance, including lightweight functional components for automotive and general engineering applications.

Key words: FDM, hybrid composites, copper filament, BDP Flax, FiberWood Brown, mechanical behavior.

1. INTRODUCTION

Additive manufacturing has evolved from a rapid prototyping technique into a mature manufacturing technology capable of producing functional engineering components. Among the available processes, fused deposition modeling (FDM) remains one of the most widely adopted due to its cost-effectiveness, ease of implementation, and compatibility with a broad range of thermoplastic materials, [1–4]. In recent years, significant attention has been directed toward the development of composite filaments designed to improve the mechanical performance and functionality of printed structures while maintaining the advantages of FDM technology, [2–4].

One of the most promising approaches involves the incorporation of metallic fillers into polymer matrices. Copper-filled PLA filaments have attracted particular interest because they provide enhanced density, thermal conductivity, and aesthetic characteristics compared with conventional PLA materials, [2, 5]. Özen et al. [5], demonstrated that copper particles significantly affect the stiffness and deformation mechanisms of FDM-printed composites, while Kyratsis et al. [7], showed that tensile performance is strongly influenced by processing parameters such as nozzle temperature, layer thickness, and flow rate. Similarly, Buj-Corral and Sivatte-Adroer [2], highlighted the influence of manufacturing conditions on the quality and internal structure of copper-filled PLA parts, whereas Chidambaram et al. [8], reported that infill configuration plays an important role in determining tensile behavior. Although these studies provide valuable information regarding copper-filled materials, they are limited to single-material systems.

At the same time, increasing environmental concerns have stimulated the development of natural-fiber-reinforced filaments for additive manufacturing. According to the review performed by Haque and Naebe [1], the mechanical performance of natural-fiber-reinforced FDM materials is influenced by factors such as fiber type, filler content, particle size, and processing conditions. Likewise, Mazzanti et al. [6], concluded that natural fibers represent a promising alternative for producing more sustainable composite filaments, although challenges related to fiber dispersion and fiber–matrix adhesion remain significant.

Among natural-fiber-based materials, wood-filled PLA composites have received considerable attention due to their renewable origin and attractive appearance. Sultana et al. [9], demonstrated that printing parameters significantly affect the tensile strength and stiffness of wood-filled PLA materials, highlighting the importance of

process optimization. More generally, Le Duigou et al. [10], reported that natural fibers can improve the stiffness of PLA-based composites when proper interfacial bonding is achieved, while Guessasma et al. [11], emphasized that heterogeneous fiber distribution may promote premature failure and anisotropic mechanical behavior.

Flax-based composites have also emerged as attractive candidates for additive manufacturing applications because flax fibers exhibit favorable mechanical properties compared with many other natural reinforcements. Tao et al. [12], reported that flax-filled PLA composites can provide improved stiffness and reduced environmental impact, whereas Ferreira et al. [13], observed increases in elastic modulus accompanied by reductions in elongation at break. These findings indicate that the reinforcing effect of flax fibers is highly dependent on the interaction between the fibers and the polymer matrix.

The quality of the fiber–matrix interface is widely recognized as one of the key factors governing the performance of natural-fiber composites. Kabir et al. [14], showed that insufficient interfacial adhesion can reduce load transfer efficiency and promote fiber pull-out during mechanical loading. Similarly, Pickering et al. [15], concluded that the mechanical response of natural-fiber-reinforced composites depends not only on the intrinsic properties of the fibers but also on the effectiveness of the bonding mechanisms developed at the interface.

In addition to material composition, the mechanical behavior of FDM-printed structures is strongly affected by manufacturing parameters. Dey and Yodo [16], demonstrated that printing orientation and raster configuration significantly influence tensile strength and failure mechanisms, while Spoerk et al. [17], reported that higher infill densities generally improve mechanical performance by reducing internal porosity. These observations underline the importance of maintaining consistent manufacturing conditions when comparing different material systems. Recent developments in additive manufacturing have also promoted the use of multi-material and hybrid structures. According to Ngo et al. [18], combining materials with different characteristics within a single printed component offers new opportunities for tailoring functional and mechanical properties. Nevertheless, despite the growing interest in hybrid manufacturing approaches, studies investigating the simultaneous use of metal-filled and natural-fiber-filled filaments remain scarce.

Although significant advances have been reported for copper-filled polymers and natural-fiber-reinforced filaments, studies on hybrid systems produced by the simultaneous extrusion of metal-filled and natural-fiber-filled materials remain limited. In particular, comparative investigations of Copper Filamet/FiberWood Brown and Copper Filamet/BDP Flax combinations under identical printing conditions are still lacking. Therefore, the novelty of this work lies in the comparative evaluation of these two hybrid material systems through tensile, bending, and impact testing. The study aims to assess the influence of different natural-fiber-based filaments on the mechanical performance of metal–natural fiber hybrid structures manufactured by FDM technology.

2. MATERIALS AND METHODS

The materials used for printing the samples consisted of two simultaneously co-extruded filament blends:

- Copper Filamet, [19] (The Virtual Foundry, USA) – FiberWood Brown [20] (Fiberlogy, Poland);
- Copper Filamet (The Virtual Foundry, USA) – BDP Flax, [21] (Extrudr, Austria).

The mechanical properties for the 3 materials used are given in Table 1

Table 1. Mechanical properties of the materials used, [19-21]

Material	σ_{\max} [MPa]	ϵ_t [%]	E [MPa]
<i>Fiber Wood Brown</i>	26	0.9	3600
<i>BDP Flax</i>	33	7.3	1573
<i>Copper Filamet</i>	15–25	1–3	3000–5000

σ_{\max} -maximum tensile strength; ϵ_t -tensional strain; E-young modulus

Copper Filamet is a composite filament composed predominantly of finely dispersed copper particles embedded within a polylactic acid (PLA) matrix. This material enables the additive manufacturing of components that can subsequently undergo post-processing operations, such as debinding and sintering, to obtain dense metallic parts with properties similar to those of conventionally manufactured copper components, [19].

BDP (Biodegradable Polymer) Flax, with a filament diameter of 1.75 mm, is a bio-based composite material that combines a biodegradable polymer derived from renewable resources with natural flax fibers. The incorporation of flax fibers enhances the material’s sustainability while providing a distinctive appearance and modified mechanical characteristics, [21].

FiberWood Brown 1.75 mm is a PLA-based composite filament containing finely distributed wood particles. The addition of wood fillers imparts a natural wood-like texture and appearance to printed parts while maintaining the ease of processing associated with conventional PLA materials, [20].

The uniaxial tensile tests and bending tests were carried out using a computerized electromechanical universal testing machine, model VTS WDW-100E, [23] (Jinan Victory Instrument Co. Ltd., China). The tensile test samples were manufactured according to ISO 527-2, Type 1B. The bending test samples were obtained according to ISO 178:2019 Plastics — Determination of flexural properties.

Impact resistance tests were carried out using a ZwickRoell HIT25P pendulum impact tester (Zwick GmbH & Co. KG, Germany). To evaluate the toughness (impact strength) of the 3D-printed specimens, the Charpy method was employed in accordance with ISO 179-1:2026 (Plastics — Determination of Charpy impact properties — Part 1: Non-instrumented impact test).

The 3D printing of the tensile test samples was performed according to a full factorial experimental design (2^3), as shown in Table 2. The three input parameters were: layer thickness, number of outer contours (shells), and the mixing ratio of materials A and B, where A represents Copper Filamet and B represents FiberWood Brown (or BDP Flax, respectively). Each parameter was investigated at two levels.

Table 2. Experimental design

Exp. No.	Layer Thickness [-1 = 0.3 mm, +1 = 0.6 mm]	Shells no [-1 = 2, +1 = 4]	Mixing ratio [-1 = 67% A, 33% B; +1 = 33% A, 67% B]
1	-1	-1	-1
2	-1	-1	+1
3	-1	+1	-1
4	-1	+1	+1
5	+1	-1	-1
6	+1	-1	+1
7	+1	+1	-1
8	+1	+1	+1

Three samples (sample a, sample b, and sample c) were printed for each experimental condition, resulting in a total of 24 samples for the Copper Filamet–FiberWood Brown blend and 24 samples for the Copper Filamet–BDP Flax blend.

3. RESULTS AND DISCUSSION

3.1 Tensile test

The tensile test results revealed a clear influence of material composition on the mechanical performance of the hybrid samples manufactured by simultaneous extrusion. All samples were produced under identical conditions, namely a printing temperature of 215°C, a bed temperature of 60°C, a grid infill pattern with 100% infill density, and a flat orientation rotated by 45° around the Z-axis. Consequently, the observed differences can be primarily attributed to the interaction between the copper-filled filament and the natural-fiber-based material, as well as to the selected layer thickness and shell configuration.

Table 3 and Table 4 summarize the average values with the associated deviations of σ_{max} (maximum tensile strength), ϵ_t (tensional strain), and E (Young's modulus) for each experiment performed with the Copper Filamet - FiberWood Brown and Copper Filamet - BDP Flax mixtures, respectively.

Table 3. Experimental results of tensile tests of samples printed with Copper Filamet - FiberWood Brown blend

Exp. no.	Sample	σ_{max} [MPa]	ϵ_t [%]	E [MPa]
1	a	14.62	1.6	1724.50
	b	14.88	1.3	1749.50
	c	15.32	1.3	1820.50
<i>Average</i>		<i>14.94±0.35</i>	<i>1.40±0.17</i>	<i>1764.83±49.80</i>
2	a	11.15	1.0	1764.50
	b	11.38	1.4	1766.50
	c	12.80	1.0	2128.50
<i>Average</i>		<i>11.78±0.89</i>	<i>1.13±0.23</i>	<i>1886.50±209.58</i>

3	a	16.62	1.6	1969.00
	b	15.88	1.3	1966.50
	c	14.62	1.7	1727.00
<i>Average</i>		<i>15.71±1.01</i>	<i>1.53±0.21</i>	<i>1887.50±139.00</i>
4	a	13.38	1.1	2174.00
	b	12.42	1.0	2138.00
	c	12.05	1.1	1812.00
<i>Average</i>		<i>12.62±0.69</i>	<i>1.07±0.06</i>	<i>2041.33±199.42</i>
5	a	17.88	1.6	1799.00
	b	17.48	1.4	1979.00
	c	15.88	1.4	1882.50
<i>Average</i>		<i>17.08±1.06</i>	<i>1.47±0.12</i>	<i>1886.83±90.08</i>
6	a	12.88	1.7	1915.00
	b	12.35	1.1	2043.50
	c	12.85	1.1	2106.50
<i>Average</i>		<i>12.69±0.30</i>	<i>1.30±0.35</i>	<i>2021.67±97.60</i>
7	a	15.00	1.7	1647.00
	b	13.32	1.1	1719.00
	c	14.02	1.3	1764.50
<i>Average</i>		<i>14.11±0.84</i>	<i>1.37±0.31</i>	<i>1710.17±59.25</i>
8	a	12.45	1.1	2003.00
	b	12.12	1.1	2017.00
	c	12.88	2.0	1912.00
<i>Average</i>		<i>12.48±0.38</i>	<i>1.40±0.52</i>	<i>1977.33±57.01</i>

Table 4. Experimental results of tensile tests of samples printed with Copper Filamet - BDP Flax blend

Exp. no.	Sample	σ_{max} [MPa]	ϵ_t [%]	E [MPa]
1	a	22.80	2.0	1946.50
	b	21.00	2.0	2429.00
	c	23.25	2.1	2474.50
<i>Average</i>		<i>22.35±1.19</i>	<i>2.03±0.06</i>	<i>2283.33±292.59</i>
2	a	15.25	2.0	2055.00
	b	17.12	1.9	2261.50
	c	16.00	1.4	2378.00
<i>Average</i>		<i>16.12±0.94</i>	<i>1.77±0.32</i>	<i>2231.50±163.58</i>
3	a	26.62	2.1	2595.00
	b	25.38	2.6	2686.00
	c	23.62	2.1	2543.50
<i>Average</i>		<i>25.21±1.51</i>	<i>2.27±0.29</i>	<i>2608.17±72.16</i>
4	a	18.38	1.4	2534.00
	b	18.00	1.7	2285.00
	c	17.62	2.0	2264.50
<i>Average</i>		<i>18.00±0.38</i>	<i>1.70±0.30</i>	<i>2361.17±150.03</i>
5	a	23.75	2.0	2627.00
	b	26.98	2.0	2640.50
	c	25.62	2.1	2603.00
<i>Average</i>		<i>25.45±1.62</i>	<i>2.03±0.06</i>	<i>2623.50±18.99</i>
6	a	17.12	1.6	2476.00
	b	16.88	1.9	2351.50
	c	15.88	2.1	2177.50
<i>Average</i>		<i>16.63±0.66</i>	<i>1.87±0.25</i>	<i>2335.00±149.93</i>
7	a	24.25	2.3	2326.50
	b	22.12	1.7	2297.00
	c	24.25	2.1	2463.00
<i>Average</i>		<i>23.54±1.23</i>	<i>2.03±0.31</i>	<i>2362.17±88.56</i>
8	a	16.50	1.4	2435.50
	b	17.00	1.7	2259.00
	c	15.62	2.0	2186.50
<i>Average</i>		<i>16.37±0.70</i>	<i>1.70±0.30</i>	<i>2293.67±128.07</i>

For the *Copper Filament–FiberWood Brown* combination, the maximum tensile strength ranged from 11.78 MPa to 17.08 MPa. The highest average value was obtained in Experiment 5, where the samples reached 17.08 ± 1.06 MPa, while the lowest strength was recorded in Experiment 2, with 11.78 ± 0.89 MPa. This corresponds to an increase of approximately 45.0%, highlighting the strong influence of the material ratio and printing strategy on the load-bearing capability of the printed structure. A consistent trend can be observed for the experiments containing the higher proportion of Component A (67% Copper Filament and 33% FiberWood Brown), which generally exhibited superior tensile strength compared with samples containing a larger proportion of FiberWood Brown. This behavior may be attributed to the higher continuity of the copper-filled phase, which improves stress transfer through the structure and reduces the detrimental effect of wood particles acting as local stress concentrators.

The influence of layer thickness was also evident. Under the optimal material composition, increasing the layer thickness from 0.3 mm to 0.6 mm led to an increase in tensile strength from 14.94 MPa (Experiment 1) to 17.08 MPa (Experiment 5), corresponding to an improvement of approximately 14.3%. Such behavior suggests that the thicker deposited roads promoted improved interlayer bonding and reduced the number of interfaces susceptible to crack initiation. Similar observations have been reported in the literature for highly filled composite filaments, where a reduction in the number of deposited layers may enhance the continuity of the load-transfer paths within the printed structure.

The elastic modulus of the *Copper Filament–FiberWood Brown* samples exhibited a different tendency. The highest stiffness values were obtained in Experiments 4 and 6, reaching 2041.33 MPa and 2021.67 MPa, respectively, whereas the lowest modulus was measured in Experiment 7 (1710.17 MPa). The difference between the maximum and minimum values was approximately 19.4%, indicating that the parameters favoring strength are not necessarily those maximizing stiffness. The higher FiberWood Brown content appears to increase rigidity while simultaneously reducing ultimate strength, most likely due to the intrinsic stiffness of the lignocellulosic particles and the reduced ability of the material to redistribute stresses before failure, Figure 1(a).

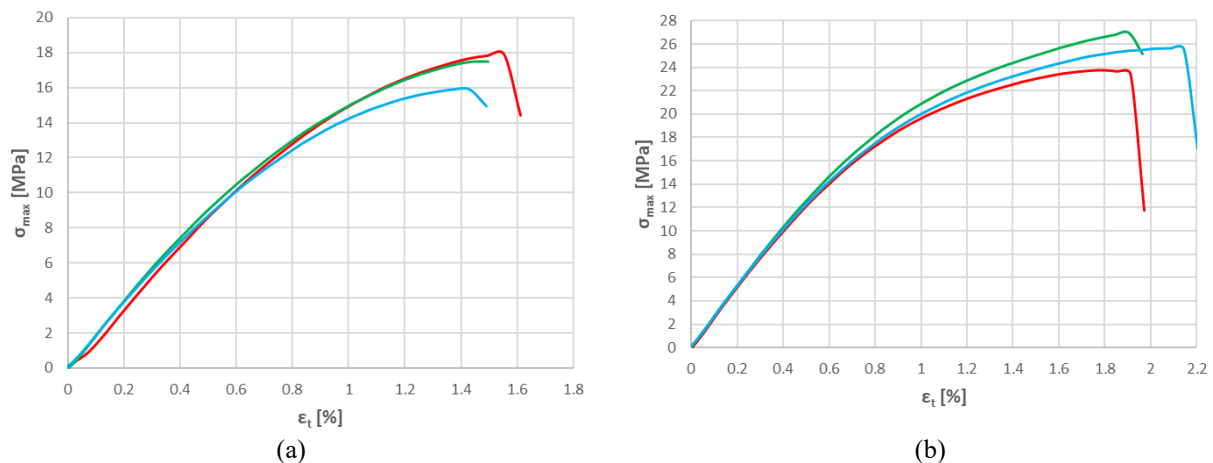


Fig. 1. Tensile test characteristic curves: (a) Copper Filament - FiberWood blend; (b) Copper Filament-BDP Flax blend

The strain at maximum stress remained relatively low for all *Copper Filament–FiberWood Brown* samples, varying between 1.07% and 1.53%. Such values are characteristic of brittle composite materials and indicate limited plastic deformation prior to fracture. The relatively narrow strain interval further suggests that changes in composition and printing parameters predominantly affected strength and stiffness rather than ductility.

A substantially different behavior was observed for the *Copper Filament–BDP Flax* hybrid samples. The maximum tensile strength varied between 16.12 MPa and 25.45 MPa, with the highest value again obtained in Experiment 5 (25.45 ± 1.62 MPa). Compared with the best-performing *Copper Filament–FiberWood Brown* configuration, the tensile strength increased by approximately 48.9%, demonstrating the superior reinforcing capability of the flax-based material. Even the lowest-performing *Copper Filament–BDP Flax* sample (16.12 MPa) exhibited a strength level comparable to or higher than most of the *FiberWood Brown* configurations.

The superior performance of the BDP Flax-containing samples can be associated with the inherently better mechanical properties of flax fibers and their more efficient stress-transfer capability within the polymer matrix. Unlike wood particles, flax fibers can contribute more effectively to load sharing, thereby delaying crack propagation and increasing the resistance of the structure to tensile loading. This observation is consistent with

previous studies reporting improved mechanical performance for flax-reinforced PLA composites compared with wood-filled systems.

The effect of material composition was again dominant. Samples containing 67% Copper Filamet and 33% BDP Flax consistently achieved tensile strengths between 22.35 MPa and 25.45 MPa, whereas increasing the BDP Flax proportion to 67% reduced strength to values between 16.12 MPa and 18.00 MPa. The decrease reached approximately 36.7% when comparing the best-performing sample (Experiment 5) with the lowest-performing configuration (Experiment 2). These results indicate that an excessive proportion of the natural-fiber-based component may disrupt the continuity of the copper-filled phase and increase the number of stress concentration sites within the structure.

The elastic modulus of the Copper Filamet–BDP Flax samples ranged from 2231.50 MPa to 2623.50 MPa, significantly exceeding the values measured for the FiberWood Brown counterparts. The highest modulus was obtained in Experiment 5, reaching 2623.50 MPa, which represents an increase of approximately 28.5% compared with the highest modulus measured for the Copper Filamet–FiberWood Brown samples. This finding confirms that the flax-based reinforcement not only improved tensile strength but also enhanced structural rigidity.

Representative stress–strain curves corresponding to Experiment 5 were selected for discussion because this configuration provided the highest average tensile strength for both material systems. The curves exhibit a typical behavior of highly filled FDM composites, characterized by an initial linear elastic region followed by a limited nonlinear deformation stage and a relatively abrupt failure. The Copper Filamet–FiberWood Brown samples reached maximum stresses of approximately 17 MPa at strains close to 1.5%, after which a rapid stress drop occurred, indicating brittle fracture. In contrast, the Copper Filamet–BDP Flax samples sustained stresses exceeding 25 MPa and achieved strains approaching 2.0–2.1% before failure. The larger area under the stress–strain curve suggests a higher capacity for energy absorption and a more efficient load-transfer mechanism within the hybrid structure, Figure 1(b).

Another noteworthy observation is the relatively small dispersion between the individual curves within each experiment. Although some variability in failure strain can be observed, particularly for the FiberWood Brown samples, the overall curve shapes remain highly consistent, indicating good repeatability of the manufacturing process. The use of a 100% grid infill, a constant nozzle temperature of 215°C, and a common deposition strategy contributed to reducing process-induced variability and enabled a reliable comparison between the two material systems.

Overall, the results demonstrate that the Copper Filamet–BDP Flax combination provides superior tensile performance compared with Copper Filamet–FiberWood Brown under identical printing conditions. The best-performing BDP Flax samples exhibited increases of approximately 49% in tensile strength, 29% in elastic modulus, and about 38% in strain at maximum stress compared with the corresponding FiberWood Brown samples. These improvements indicate that flax-based reinforcement offers a more effective balance between stiffness and strength, making it a promising candidate for the development of multifunctional hybrid materials manufactured through multi-material FDM technology.

3.2. Bending test

The bending test results revealed a clear influence of material composition on the flexural performance of the hybrid samples manufactured by simultaneous extrusion. Tables 5 and 6 summarize the average values and associated deviations of σ_{\max} , ϵ_f and E for each experiment performed with the Copper Filamet–FiberWood Brown and Copper Filamet–BDP Flax mixtures, respectively.

For the Copper Filamet–FiberWood Brown combination, the maximum bending strength ranged from 6.27 MPa to 11.03 MPa. The highest average value was obtained in Experiment 3, where the samples reached 11.03 ± 0.81 MPa, while the lowest strength was recorded in Experiment 2, with 6.27 ± 2.24 MPa. This corresponds to an increase of approximately 76.0%, highlighting the strong influence of the material ratio and printing strategy on the flexural load-bearing capability of the printed structure. A consistent trend can be observed for the experiments containing the higher proportion of Component A (67% Copper Filamet and 33% FiberWood Brown), which generally exhibited superior bending strength compared with samples containing a larger proportion of FiberWood Brown. This behavior may be attributed to the greater continuity of the copper-filled phase, which promotes more efficient stress transfer during bending and reduces the detrimental effect of wood particles acting as local stress concentrators.

The influence of shell number was also evident. Under the same material composition and layer thickness, increasing the number of shells from two to four generally resulted in higher bending strength. The best-performing configuration (Experiment 3) combined the higher Copper Filamet content with four shells and a layer thickness of 0.3 mm, suggesting that the larger amount of perimeter material contributed to strengthening the outer regions of the sample, where the highest tensile and compressive stresses develop during flexural loading.

The elastic modulus of the Copper Filament–FiberWood Brown samples ranged from 1202.00 MPa to 1572.17 MPa. The highest stiffness was obtained in Experiment 1, whereas the lowest modulus was recorded in Experiment 2, corresponding to a difference of approximately 30.8%. Unlike bending strength, the modulus did not exhibit a clear monotonic dependence on a single processing parameter, indicating that stiffness is governed by the combined influence of material composition, interlayer bonding, and internal architecture. The strain at maximum stress remained relatively low for all Copper Filament–FiberWood Brown samples, varying between 0.80% and 1.47%. Such values are characteristic of brittle composite materials and indicate limited deformation before failure.

A substantially different behavior was observed for the Copper Filament–BDP Flax hybrid samples. The maximum bending strength varied between 11.50 MPa and 23.07 MPa, with the highest value again obtained in Experiment 3 (23.07 ± 1.45 MPa). Compared with the best-performing Copper Filament–FiberWood Brown configuration, the bending strength increased by approximately 109%, demonstrating the superior reinforcing capability of the flax-based material. Even the lowest-performing Copper Filament–BDP Flax sample exhibited a flexural strength comparable to or higher than most of the FiberWood Brown configurations.

Table 5. Experimental results of bending tests, samples printed with the Copper Filament – Fiber Wood Brown mixture

Exp. no.	Sample	σ_{\max} [MPa]	ϵ_f [%]	E [MPa]
1	a	11.50	1.10	1442.50
	b	10.10	1.00	1831.50
	c	10.10	1.30	1442.50
<i>Average</i>		<i>10.57±0.81</i>	<i>1.13±0.15</i>	<i>1572.17±224.59</i>
2	a	8.70	1.00	1442.50
	b	4.30	0.50	1442.50
	c	5.80	0.90	721.00
<i>Average</i>		<i>6.27±2.24</i>	<i>0.80±0.26</i>	<i>1202.00±416.56</i>
3	a	11.50	1.30	1442.50
	b	10.10	1.30	1452.50
	c	11.50	1.20	1442.50
<i>Average</i>		<i>11.03±0.81</i>	<i>1.27±0.06</i>	<i>1445.83±5.77</i>
4	a	8.70	1.00	1442.50
	b	5.80	0.70	1442.50
	c	8.70	0.90	1442.50
<i>Average</i>		<i>7.73±1.67</i>	<i>0.87±0.15</i>	<i>1442.50±0.00</i>
5	a	10.10	1.40	1442.50
	b	10.10	1.20	1442.50
	c	10.10	1.10	1442.50
<i>Average</i>		<i>10.10±0.00</i>	<i>1.23±0.15</i>	<i>1442.50±0.00</i>
6	a	7.20	1.10	1442.50
	b	7.20	1.20	1442.50
	c	7.20	1.10	1442.50
<i>Average</i>		<i>7.20±0.00</i>	<i>1.13±0.06</i>	<i>1442.50±0.00</i>
7	a	10.10	1.50	1442.50
	b	10.10	1.20	1045.50
	c	10.10	1.70	1216.00
<i>Average</i>		<i>10.10±0.00</i>	<i>1.47±0.25</i>	<i>1234.67±199.16</i>
8	a	7.20	1.10	1442.50
	b	8.70	1.30	1442.50
	c	7.20	1.20	1442.50
<i>Average</i>		<i>7.70±0.87</i>	<i>1.20±0.10</i>	<i>1442.50±0.00</i>

σ_{\max} –maximum bending stress; ϵ_f –bending stress; E–Young’s modulus

Representative bending stress–strain curves corresponding to Experiment 3 were selected for discussion because this configuration provided the highest average flexural strength for both material systems. The curves exhibit a typical behavior of highly filled FDM composites, characterized by an initial linear elastic region followed by a relatively abrupt failure after reaching the maximum stress. The Copper Filament–FiberWood Brown samples reached maximum stresses of approximately 11 MPa at strains close to 1.2–1.3%, after which a sudden stress drop occurred, indicating brittle fracture. In contrast, the Copper Filament–BDP Flax samples sustained stresses exceeding 23 MPa and achieved strains approaching 1.8–1.9% before failure. The larger area under the stress–

strain curves suggests a greater capacity for energy absorption and a more efficient load-transfer mechanism within the hybrid structure, Figure 2.

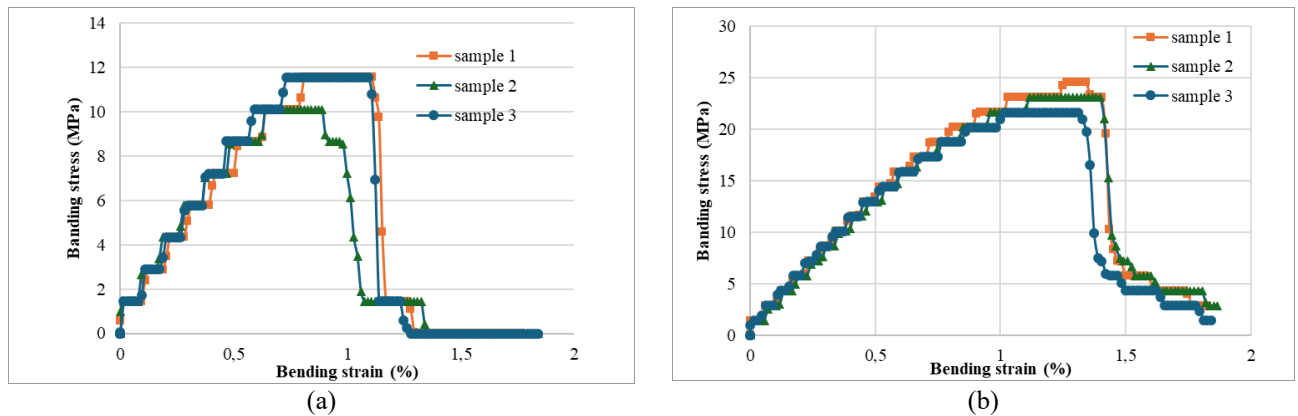


Fig. 2. Bending test characteristic curves: (a) Copper Filament - FiberWood blend; (b) Copper Filament-BDP Flax blend

The superior performance of the BDP Flax-containing samples can be associated with the inherently better mechanical properties of flax fibers and their more efficient stress-transfer capability within the polymer matrix. Unlike wood particles, flax fibers contribute more effectively to load sharing during bending and delay crack propagation, thereby increasing the resistance of the structure to flexural loading. This observation is consistent with previous studies reporting improved mechanical performance for flax-reinforced PLA composites compared with wood-filled systems.

The effect of material composition was again dominant. Samples containing 67% Copper Filament and 33% BDP Flax consistently achieved the highest bending strengths, reaching values between 19.23 MPa and 23.07 MPa, whereas increasing the BDP Flax proportion to 67% reduced strength to values between 11.50 MPa and 14.40 MPa. The decrease reached approximately 50.2% when comparing the best-performing sample (Experiment 3) with the lowest-performing configuration (Experiment 6). These results indicate that although flax fibers provide effective reinforcement, an excessive proportion of the natural-fiber-based component may reduce the continuity of the copper-filled phase and increase the number of stress concentration sites within the structure.

The elastic modulus of the Copper Filament–BDP Flax samples ranged from 1698.83 MPa to 2676.17 MPa, significantly exceeding the values measured for the FiberWood Brown counterparts. The highest modulus was obtained in Experiment 3, reaching 2676.17 MPa, which represents an increase of approximately 70.2% compared with the highest modulus measured for the Copper Filament–FiberWood Brown samples. This finding confirms that the flax-based reinforcement not only improved bending strength but also enhanced structural rigidity.

Table 6. Experimental results of bending tests, samples printed with the Copper Filament - BDP Flax

Exp. no.	Sample	σ_{max} [MPa]	ϵ_r [%]	E [MPa]
1	a	20.20	1.80	2663.50
	b	17.30	1.80	2298.50
	c	20.20	1.80	2786.00
<i>Average</i>		<i>19.23±1.67</i>	<i>1.80±0.00</i>	<i>2582.67±253.60</i>
2	a	11.50	1.40	2163.50
	b	13.00	1.60	2163.50
	c	13.00	1.50	2155.00
<i>Average</i>		<i>12.50±0.87</i>	<i>1.50±0.10</i>	<i>2160.67±4.91</i>
3	a	24.50	1.80	2692.50
	b	23.10	1.90	2777.50
	c	21.60	1.80	2558.50
<i>Average</i>		<i>23.07±1.45</i>	<i>1.83±0.06</i>	<i>2676.17±110.41</i>
4	a	14.40	1.50	2142.00
	b	14.40	1.60	2146.00
	c	14.40	1.60	2173.50
<i>Average</i>		<i>14.40±0.00</i>	<i>1.57±0.06</i>	<i>2153.83±17.15</i>
5	a	18.70	1.90	2163.50
	b	20.20	1.80	2163.50

	c	18.70	1.90	2163.50
<i>Average</i>		<i>19.20±0.87</i>	<i>1.87±0.06</i>	<i>2163.50±0.00</i>
6	a	11.50	1.70	2159.00
	b	11.50	1.80	1442.50
	c	11.50	1.80	1575.00
<i>Average</i>		<i>11.50±0.00</i>	<i>1.77±0.06</i>	<i>1725.50±381.22</i>
7	a	20.20	1.90	2163.50
	b	20.20	2.20	2029.00
	c	20.20	2.10	2110.00
<i>Average</i>		<i>20.20±0.00</i>	<i>2.07±0.15</i>	<i>2100.83±67.72</i>
8	a	13.00	1.80	1882.00
	b	13.00	1.80	1448.00
	c	11.50	1.80	1766.50
<i>Average</i>		<i>12.50±0.87</i>	<i>1.80±0.00</i>	<i>1698.83±224.77</i>

σ_{\max} -maximum bending stress; ϵ_f -bending stress; E-Young's modulus

Another noteworthy observation is the relatively small dispersion between the individual curves within each experiment. Although some variability can be observed, particularly for the FiberWood Brown samples, the overall curve shapes remain highly consistent, indicating good repeatability of the manufacturing process. The use of identical processing conditions and a common deposition strategy contributed to reducing process-induced variability and enabled a reliable comparison between the two material systems.

Overall, the results demonstrate that the Copper Filament–BDP Flax combination provides superior flexural performance compared with Copper Filament–FiberWood Brown under identical printing conditions. The best-performing BDP Flax samples exhibited increases of approximately 109% in bending strength, 70% in flexural modulus, and about 41% in strain at maximum stress compared with the corresponding FiberWood Brown samples. These improvements indicate that flax-based reinforcement offers a more effective balance between stiffness and strength, making it a promising candidate for the development of multifunctional hybrid materials manufactured through multi-material FDM technology.

3.3. Impact test

A comparison between the Copper Filament–BDP Flax and Copper Filament–FiberWood composites revealed distinct differences in their impact behaviour, Table 7 and Table 8. In both material systems, the impact properties were strongly influenced by the selected printing parameters, confirming the importance of process optimization in additively manufactured composites. The highest impact performance was obtained for Sample 3 of the Copper Filament–BDP Flax composite, which reached an absorbed energy of 0.520 ± 0.263 J and an impact resilience of 12.56 ± 5.58 kJ/m². These values indicate an enhanced capacity for energy dissipation under dynamic loading conditions and suggest an efficient interaction between the copper-filled matrix and the flax reinforcement.

Table 7. Experimental results of impact tests, samples printed with the Copper Filament – FiberWood

Exp. no.	Sample	E_c (J)	β (°)	a_{cU} (kJ/m ²)
1	a	0.253	88.02	6.33
	b	0.319	83.07	7.98
	c	0.171	94.14	4.28
<i>Average</i>		<i>0.248±0.074</i>	<i>88.41±5.55</i>	<i>6.19±1.85</i>
2	a	0.197	92.16	4.93
	b	0.248	88.38	6.20
	c	0.142	96.30	3.55
<i>Average</i>		<i>0.196±0.053</i>	<i>92.28±3.96</i>	<i>4.89±1.33</i>
3	a	0.223	90.27	5.58
	b	0.237	89.19	5.93
	c	0.179	93.51	4.48
<i>Average</i>		<i>0.213±0.030</i>	<i>90.99±2.25</i>	<i>5.33±0.76</i>
4	a	0.195	92.34	4.88
	b	0.185	93.06	4.63
	c	0.197	92.16	4.93
<i>Average</i>		<i>0.192±0.006</i>	<i>92.52±0.48</i>	<i>4.81±0.16</i>
5	a	0.170	94.23	4.25
	b	0.158	95.13	3.95

	c	0.182	93.33	4.55
<i>Average</i>		<i>0.170±0.012</i>	<i>94.23±0.90</i>	<i>4.25±0.30</i>
6	a	0.233	89.55	5.83
	b	0.179	93.51	4.48
	c	0.277	86.22	6.93
<i>Average</i>		<i>0.230±0.049</i>	<i>89.76±3.65</i>	<i>5.74±1.23</i>
7	a	0.190	92.70	4.75
	b	0.276	86.31	6.90
	c	0.171	94.14	4.28
<i>Average</i>		<i>0.212±0.056</i>	<i>91.05±4.17</i>	<i>5.31±1.40</i>
8	a	0.195	92.34	4.88
	b	0.345	81.18	8.63
	c	0.189	92.79	4.73
<i>Average</i>		<i>0.243±0.088</i>	<i>88.77±6.58</i>	<i>6.08±2.21</i>

E_c -absorbed energy; β -inclination angle; a_{cU} -impact resilience

Compared to the Copper Filament–FiberWood composite, the BDP Flax-based samples generally exhibited superior impact resistance, indicating that the flax reinforcement contributed more effectively to toughness enhancement. This behavior can be attributed to the fibrous structure of flax, which may promote crack bridging and delay crack propagation during impact loading. Furthermore, the relatively high resilience values recorded for Samples 7 and 8 of the Copper Filament–BDP Flax composite (11.07 kJ/m² and 10.38 kJ/m², respectively) further support the beneficial effect of flax reinforcement on impact performance.

In contrast, the Copper Filament–FiberWood composite showed lower impact resistance, although certain parameter combinations still provided satisfactory energy absorption capabilities. The reduced performance may be associated with the morphology of the wood particles, which can act as stress concentration sites and facilitate crack initiation under sudden loading. Nevertheless, the results demonstrate that both composites benefit from optimized printing conditions, with the Copper Filament–BDP Flax system exhibiting the most favorable balance between energy absorption and impact toughness.

Table 8. Experimental results of impact tests, samples printed with the Copper Filament – BDP Flax

Exp. no.	Sample	E_c (J)	β (°)	a_{cU} (kJ/m ²)
1	a	0.303	102.78	7.58
	b	0.406	76.50	10.15
	c	0.501	69.12	12.53
<i>Average</i>		<i>0.403±0.099</i>	<i>82.80±17.69</i>	<i>10.08±2.48</i>
2	a	0.279	86.13	6.98
	b	0.341	81.45	8.53
	c	0.276	86.31	6.90
<i>Average</i>		<i>0.299±0.037</i>	<i>84.63±2.76</i>	<i>7.47±0.92</i>
3	a	0.443	73.71	11.08
	b	0.274	86.49	6.85
	c	0.790	43.02	19.75
<i>Average</i>		<i>0.502±0.263</i>	<i>67.74±22.34</i>	<i>12.56±6.58</i>
4	a	0.208	91.35	5.20
	b	0.357	80.28	8.93
	c	0.294	84.96	7.35
<i>Average</i>		<i>0.286±0.075</i>	<i>85.53±5.56</i>	<i>7.16±1.87</i>
5	a	0.437	74.16	10.93
	b	0.354	80.46	8.85
	c	0.397	77.22	9.93
<i>Average</i>		<i>0.396±0.042</i>	<i>77.28±3.15</i>	<i>9.90±1.04</i>
6	a	0.292	85.14	7.30
	b	0.337	81.72	8.43
	c	0.299	84.60	7.48
<i>Average</i>		<i>0.309±0.024</i>	<i>83.82±1.84</i>	<i>7.73±0.61</i>
7	a	0.402	76.86	10.05
	b	0.501	69.12	12.53
	c	0.425	75.06	10.63

<i>Average</i>		<i>0.443±0.052</i>	<i>73.68±4.05</i>	<i>11.07±1.30</i>
8	a	0.412	76.05	10.30
	b	0.299	84.60	7.48
	c	0.534	66.51	13.35
<i>Average</i>		<i>0.415±0.118</i>	<i>75.72±9.05</i>	<i>10.38±2.94</i>

E_c -absorbed energy; β -inclination angle; a_{cU} -impact resilience

4. CONCLUSIONS

For both material systems, the highest tensile properties were obtained with 67% Copper Filamet, highlighting the importance of the metal-filled phase continuity for efficient stress transfer. Among all tested configurations, the Copper Filamet–BDP Flax combination showed the best overall tensile performance, reaching a tensile strength of 25.45 MPa and an elastic modulus of 2623.50 MPa. Compared with the best Copper Filamet–FiberWood Brown samples, the BDP Flax hybrids exhibited improvements of approximately 49% in tensile strength and 29% in stiffness. Although both material systems displayed predominantly brittle behavior, the BDP Flax composites showed higher strain at failure and greater energy absorption capacity.

The flexural properties were significantly influenced by both material composition and printing parameters. The best results were obtained for samples containing 67% Copper Filamet and 33% reinforcement material, printed with a layer thickness of 0.3 mm and four shells. The Copper Filamet–BDP Flax hybrids consistently outperformed the FiberWood Brown counterparts, achieving increases of approximately 109% in flexural strength and 70% in flexural modulus.

Impact performance was also strongly dependent on material composition and processing conditions. The Copper Filamet–BDP Flax composites exhibited the highest impact resistance, demonstrating superior toughness and energy absorption compared with the FiberWood-based materials. The results confirm that appropriate combinations of material ratio, layer thickness, and shell number can substantially improve the mechanical behavior of multi-material FDM composites.

Overall, the findings demonstrate that the Copper Filamet–BDP Flax combination is a promising sustainable material system for additive manufacturing applications requiring enhanced tensile, flexural, and impact properties. The investigated composites show potential for lightweight automotive components, consumer products, customized tooling, and other low- to moderate-load engineering applications.

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