

SUSTAINABLE PRODUCT DESIGN USING BIO-BASED MATERIALS: A COMPARATIVE ANALYSIS BETWEEN PLA AND WOOD COMPOSITES

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This paper investigates the potential of bio-based materials in sustainable product design through a comparative analysis between standard PLA and wood-based composite materials. Experimental evaluations were conducted using hardness (Shore D) and surface roughness measurements to assess mechanical performance. The results indicate that wood-based composites exhibit properties comparable to synthetic materials, while offering additional environmental and aesthetic advantages. The study highlights the feasibility of replacing conventional plastics with bio-based alternatives in design and manufacturing processes, contributing to sustainable development and eco-friendly industrial practices.

Keywords: sustainable design, bio-based materials, PLA, wood composite, surface roughness, hardness, 3D printing

1. Introduction

Sustainable development has become a central objective in contemporary engineering and industrial design, driven by the need to reduce environmental impact while maintaining product performance and economic viability. In this context, the transition from conventional synthetic materials to bio-based alternatives represents a key research direction within circular economy and eco-design frameworks. Eco-design is recognized as a major driver for innovation in sustainable product development [1], while its integration within total

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environmental quality management emphasizes the importance of addressing environmental aspects throughout the entire product lifecycle [2]. At the same time, broader industrial strategies highlight the role of resource efficiency and global knowledge integration [3].

Recent studies underline the importance of systemic approaches for evaluating the resilience and environmental performance of sustainable systems [4], as well as the growing role of advanced technologies in supporting sustainable practices. The integration of innovative engineering solutions, including robotic systems and digital technologies such as blockchain and IoT, contributes to improved efficiency, transparency, and traceability in production systems [5], [6]. In parallel, life cycle assessment studies confirm the environmental and circularity advantages of bio-based materials [7], [8], while experimental investigations remain essential for validating material behavior under controlled conditions [9].

Bio-based materials have gained increasing attention due to their renewable origin, reduced environmental footprint, and compatibility with additive manufacturing processes. Among these, polylactic acid (PLA) and wood-based composite filaments represent promising solutions for sustainable product development, particularly in 3D printing applications. While PLA is widely used due to its biodegradability and ease of processing, wood-based composites provide additional aesthetic and sensory benefits. Previous studies have demonstrated that bio-based composites can achieve performance levels comparable to conventional materials [10], while natural resins and plant-derived materials continue to be explored as viable engineering alternatives [11]. Furthermore, the evaluation of mechanical behavior remains essential in material selection, as highlighted by research on degradation mechanisms and the influence of mechanical characteristics on material performance [12], [13].

Beyond mechanical performance, recent research emphasizes the importance of sensory design in product development. The integration of sensorial properties represents a key direction in user-centered engineering [14], supported by studies demonstrating its role in improving product development methodologies [15]. This approach extends traditional design practices by incorporating multisensory interaction and user experience considerations [16]. Sensory evaluation plays a key role in understanding user interaction with materials, particularly in terms of tactile response and surface characteristics [17], while advanced tactile sensing technologies enable more precise quantification of these interactions [18]. In addition, olfactory stimuli contribute to shaping user perception [19], while the visual and material properties of sustainable products significantly influence consumer trust and purchase intention [20], [21]. Practical applications further demonstrate the effectiveness of sensory-based design approaches in enhancing product functionality and user experience [22].

Despite this progress, the literature still lacks comparative experimental studies evaluating the mechanical performance of bio-based materials under similar processing conditions, limiting their integration into product design. Most contributions focus on material development or isolated property assessment, without providing a structured framework for informed material selection, although engineering research emphasizes its importance for ensuring efficiency and functional performance in specific applications [23], [24], [25].

In this context, the present study investigates the feasibility of replacing conventional synthetic materials with bio-based alternatives through a comparative analysis of standard PLA and a wood-based composite, focusing on hardness and surface roughness as key indicators of performance and user interaction. The originality of this research lies in the development of an experimentally validated framework that integrates material testing with design-oriented evaluation, supporting sustainable material selection while demonstrating comparable performance alongside environmental, aesthetic, and sensory advantages.

2. Materials and methods

This section presents the materials and experimental methodology used to evaluate the mechanical and surface properties of the analyzed samples, under controlled laboratory conditions to ensure reproducibility and comparability of results.

2.1. Materials

The experimental study was conducted using two materials commonly employed in additive manufacturing, selected based on their relevance for sustainable product design:

- **Standard PLA (Polylactic Acid)** – a bio-derived thermoplastic characterized by good rigidity and ease of processing;
- **Wood-based composite (WOOD)** – a bio-based material consisting of approximately 70% PLA and 30% recycled wood particles.

Both materials were used in filament form (1.75 mm diameter) and processed under identical conditions to allow direct comparison of their physical-mechanical behavior. The resulting samples are illustrated in Fig.1.

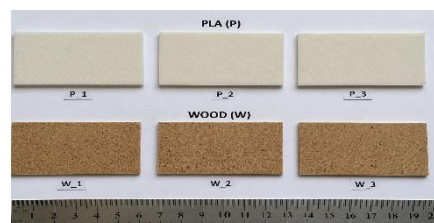


Fig. 1. Samples made of PLA (P₁–P₃) and wood-based composite (W₁–W₃)

The selected materials ensure comparable processing conditions while enabling the evaluation of ecological and sensory advantages associated with the wood-based composite.

2.2. Sample preparation

Samples were manufactured using Fused Deposition Modeling (FDM) based on CAD models developed in SolidWorks, under controlled laboratory conditions. The filament used in the fabrication process is shown in Fig. 2.



Fig. 2. Filaments used in the fabrication of experimental samples

A total of six samples were produced: three from PLA (P_1 – P_3) and three from the wood-based composite (W_1 – W_3). Each specimen had dimensions of $60 \times 40 \times 6$ mm and was printed layer-by-layer, followed by stabilization at room temperature.

Printing parameters were kept constant for both materials to ensure comparability: nozzle diameter 0.4 mm, layer height 0.2 mm, printing temperature 200–210°C (PLA) / 200°C (WOOD), printing speed 50 mm/s, and infill density 100%. All samples were printed horizontally (layers parallel to the main surface) to ensure consistent surface characteristics. After fabrication, all samples were visually inspected to confirm the absence of defects such as delamination, warping, or surface discontinuities.

2.3. Experimental procedure

The experimental evaluation focused on hardness and surface roughness, as key indicators of mechanical performance and surface behavior.

Hardness measurement

Hardness was measured using a Shore D durometer (Model HD3000), in accordance with ISO 868. The device was placed on a stable surface, and measurements were performed individually for each sample. For each sample (P_1 – P_3 , W_1 – W_3), a total of six measurements were conducted, consisting of three instantaneous values and three stabilized values recorded after a constant application time of 7 seconds. The experimental setup is presented in Fig. 3.



Fig. 3. Experimental setup for hardness measurements on PLA and wood-based samples

Indentation was applied perpendicularly to ensure uniform pressure. Reported values represent averages, reducing random variability.

Surface roughness measurement

Surface roughness was evaluated using a 3D contact profilometer with an inductive sensor. Measurements were performed directly on the printed surfaces without post-processing, using the Ra parameter. Multiple measurements were taken in different directions relative to the printing layers to capture surface morphology variations. Data were processed using ALTISURF and ALTIMAP software, and average values were calculated for each sample.

2.4. Data analysis

Experimental data were analyzed using a comparative approach between PLA (P_1 – P_3) and wood-based samples (W_1 – W_3). For each parameter, average values and measurement variability were considered to evaluate consistency and repeatability. The analysis focused on identifying similarities and differences between materials, as well as correlations between hardness and surface roughness, in relation to their relevance for product design and material selection. All measurements were performed under identical conditions to ensure reliability, while potential sources of error were minimized through multiple measurements and averaging.

Although the present study is based on a comparative experimental approach, particular attention was given to measurement consistency through repeated testing and averaging. The importance of statistical indicators such as standard deviation and data variability is acknowledged, and these aspects will be considered in future research to further enhance data interpretation and result robustness.

3. Results and Discussion

This section presents the experimental results obtained from hardness and surface roughness measurements, followed by a comparative analysis of the

investigated materials, interpreted in relation to sustainable product design and material selection.

3.1. Hardness analysis

The hardness measurements indicate a high degree of similarity between the wood-based composite (WOOD) and the synthetic PLA material. The results summarized in Table 1 show that the average Shore D values are very close for all tested samples.

Table 1

Hardness results for wood and plastic materials				
Material types and samples number	Hardness Instant Shore	Average Hardness Instant Shore	Hardness Stabilizes Shore	Average Hardness Stabilizes Shore
	[Shore D]	[Shore D]	[Shore D]	[Shore D]
Wood bio-based material (W ₁)	73	73,5	71,5	71,17
	73,5		71	
	74		71	
Wood bio-based material (W ₂)	73,5	73,67	71	71,33
	74		72	
	73,5		71	
Wood bio-based material (W ₃)	73,5	73,5	71,5	71,83
	73,5		72	
	73,5		72	
Synthetic plastic material (P ₁)	74	73,33	72	71,33
	73		71	
	73		71	
Synthetic plastic material (P ₂)	73	73,5	71	71,33
	74		72	
	73,5		71	
Synthetic plastic material (P ₃)	74	73,33	72	71,83
	72,5		72	
	73,5		71,5	

The instant hardness values are clustered around 73–74 Shore D, while the stabilized values range between 71–72 Shore D. The variation between samples remains limited (approximately ± 0.5 Shore D), indicating good consistency and measurement repeatability.

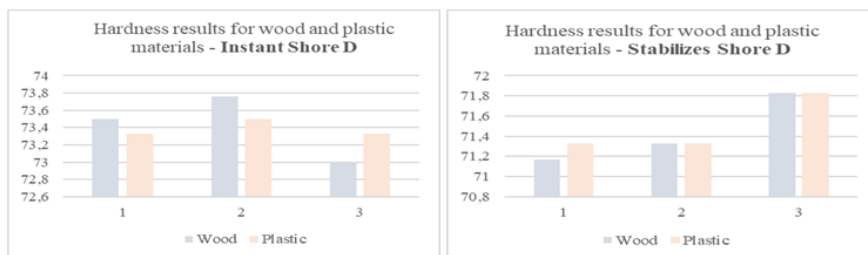


Fig. 4. Comparison of hardness values between wood-based composite and PLA

The wood-based composite exhibits hardness values comparable to PLA, demonstrating that the incorporation of wood particles does not significantly affect resistance to indentation and that the material maintains mechanical performance at a level similar to conventional polymers. The comparative results are illustrated in Fig. 4, which highlights the minimal differences between the average values and the similar trend followed by both materials.

A more detailed comparison between corresponding samples (W_1-P_1 , W_2-P_2 , W_3-P_3), presented in Figs. 5–7, confirms that deviations between paired samples are negligible.

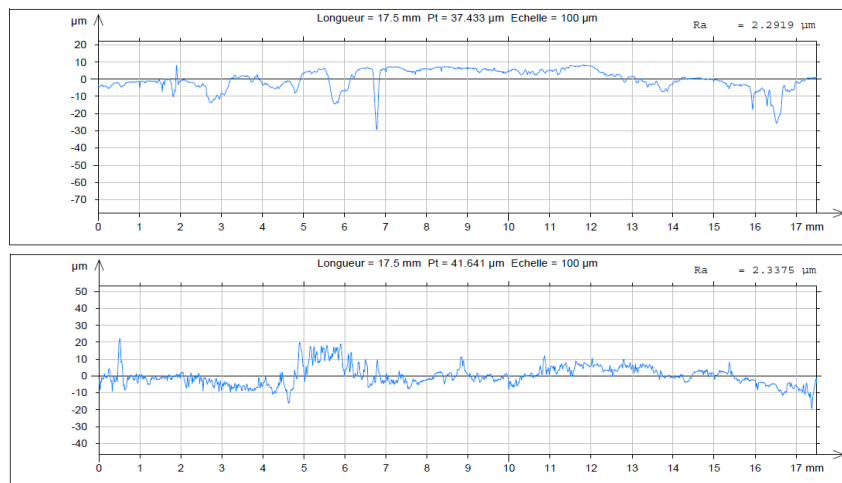


Fig. 5. Comparative hardness results for samples W_1 and P_1

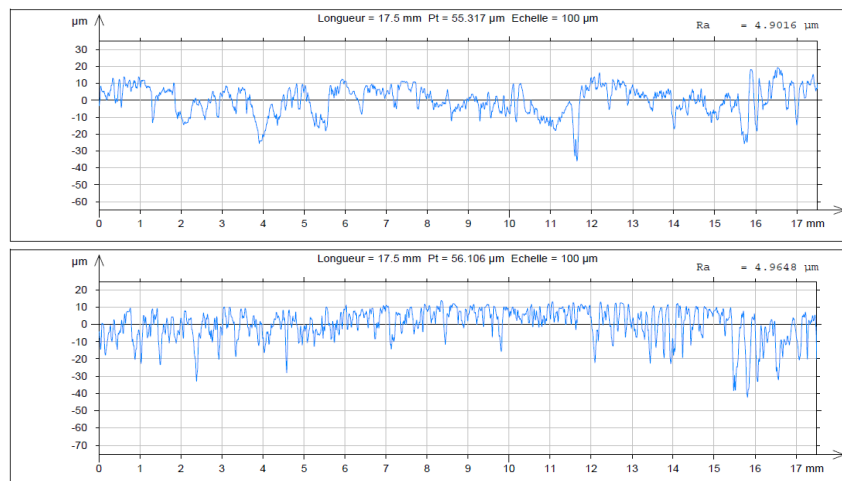


Fig. 6. Comparative hardness results for samples W_2 and P_2

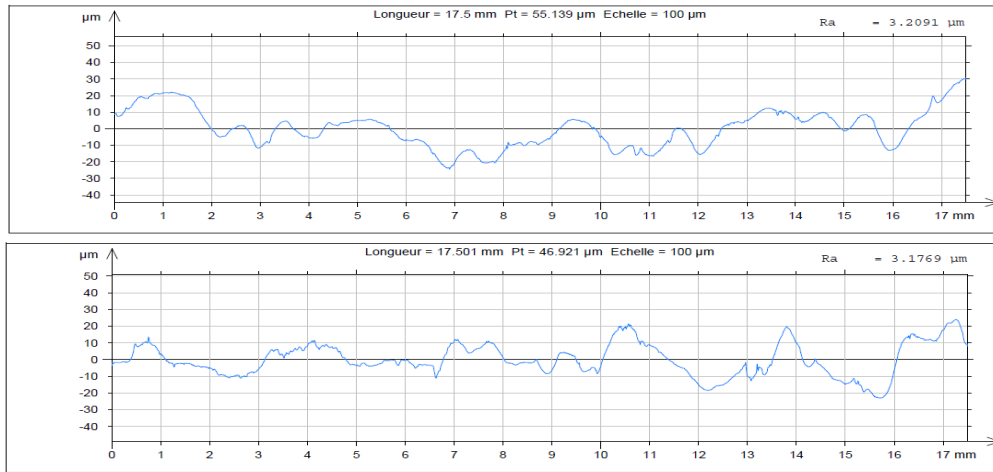


Fig. 7. Comparative hardness results for samples W₃ and P₃

From a design perspective, these results are relevant, as hardness is directly associated with durability and resistance to mechanical wear, supporting the use of wood-based composites in applications requiring mechanical stability.

3.2. Surface roughness analysis

Surface roughness measurements (Ra) show comparable behavior between the wood-based composite and PLA, as presented in Table 2.

Table 2

Roughness results for wood and plastic materials

Material types	Samples Number	Roughness [μm] – (W)	Roughness [μm] – (P)	Samples Number	Material types
Wood bio-based material (W)	W₁	2.2919	2.3375	P₁	Synthetic plastic material (P)
Wood bio-based material (W)	W₂	4.9016	4.9648	P₂	Synthetic plastic material (P)
Wood bio-based material (W)	W₃	3.2091	3.1769	P₃	Synthetic plastic material (P)

The values fall within a similar range (approximately 2.2–5.0 μm), with minimal deviations between corresponding samples (generally below 0.1–0.2 μm), indicating a high degree of similarity between the two materials.

The slightly more heterogeneous surface of the wood-based composite can be attributed to the presence of natural wood particles within the polymer matrix; however, this does not significantly affect overall roughness values.

From a functional perspective, surface roughness influences friction, wear, and tactile perception. As shown in Fig. 8, the wood-based composite exhibits surface characteristics comparable to PLA, while also providing enhanced sensory qualities, such as a more natural texture.



Fig. 8. Comparison of surface roughness values between wood-based composite and PLA

The Ra parameter was selected due to its widespread use in engineering practice and its relevance for evaluating surface quality in additively manufactured components. However, a more comprehensive surface characterization could be achieved by including additional parameters such as Rz or three-dimensional surface analysis, which will be considered in future studies.

3.3. Comparative interpretation

The combined analysis of hardness and surface roughness confirms that the wood-based composite performs at a level comparable to standard PLA in terms of key physical-mechanical properties. Both materials exhibit similar hardness (73–74 Shore D instant, 71–72 Shore D stabilized) and roughness values (2.2–5.0 μm), with minimal deviations between corresponding samples, supporting the consistency of the experimental results.

This outcome is particularly relevant for sustainable product design, demonstrating that bio-based materials can be integrated into manufacturing processes without compromising essential performance criteria.

The results also highlight the potential of wood-based composites as alternatives to synthetic materials in applications such as product prototyping, consumer goods, interior design elements, and lightweight construction components.

From an application perspective, these findings highlight the potential use of wood-based composites in various industrial fields, including rapid prototyping, customized consumer products, interior design elements, and lightweight components. The combination of mechanical performance and enhanced aesthetic and sensory properties make these materials particularly suitable for user-centered design applications.

3.4. Discussion of results

The results confirm that incorporating natural fibers into polymer matrices can produce materials with balanced mechanical and surface properties. The analyzed wood-based composite meets the functional requirements defined by hardness and roughness while providing additional ecological and sensory value.

These findings support the possibility of reducing reliance on fully synthetic materials in design and manufacturing, contributing to lower environmental impact without compromising performance.

From a design perspective, the slightly heterogeneous surface structure of the composite may be considered advantageous, enhancing tactile and visual qualities relevant for user-centered and sensory design applications.

However, the study is limited to a restricted set of properties. Further investigation of tensile strength, impact resistance, and long-term durability is necessary for a comprehensive evaluation.

Despite these limitations, the experimental methodology provides a reproducible and scalable framework that can be extended to other bio-based materials and integrated into multidisciplinary research involving mechanical, environmental, and sensory analysis.

However, this study is limited to laboratory conditions, and further validation in real industrial environments is required to assess material performance in practical applications. In addition, factors such as production cost, material availability, and scalability are essential for the industrial adoption of bio-based materials and should be considered in future research.

Moreover, although bio-based materials are generally associated with reduced environmental impact, a comprehensive evaluation through Life Cycle Assessment (LCA) is necessary to quantify their sustainability performance. This aspect is beyond the scope of the present study and represents an important direction for future research.

4. Conclusions

This study demonstrates that bio-based materials represent a viable and sustainable alternative to conventional polymers, providing comparable mechanical performance while supporting the transition toward environmentally responsible product design. The feasibility of replacing conventional synthetic materials with bio-based alternatives was investigated through a comparative experimental analysis of standard PLA and a wood-based composite. The results indicate that the analyzed composite exhibits hardness and surface roughness values comparable to those of PLA, with minimal variation between samples, confirming that the incorporation of wood particles into the polymer matrix does not significantly affect mechanical performance or surface quality.

These findings validate the use of wood-based composites as viable substitutes for conventional plastics in engineering and design applications, including product prototyping, consumer goods, and interior design components.

A key contribution of this research is the development of a reproducible experimental framework that integrates controlled material testing with design-oriented evaluation criteria, supporting informed material selection in sustainable product development. Beyond mechanical performance, the analyzed composite provides additional advantages related to reduced environmental impact, enhanced aesthetic qualities, and improved sensory characteristics, reinforcing its relevance in eco-design and circular economy strategies. Overall, the results confirm that the transition toward bio-based materials is both technically feasible and environmentally beneficial, without compromising functional requirements.

Future research should extend the analysis to additional mechanical properties (e.g., tensile strength and impact resistance), long-term durability, and Life Cycle Assessment (LCA), while focusing on the validation of these materials in real industrial applications. In addition, aspects such as economic feasibility, production scalability and advanced statistical analysis and sensory evaluation methods will contribute to a more comprehensive understanding of the performance and sustainability of bio-based materials in product design.

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