Journal of Building Material Science
https://journals.bilpubgroup.com/index.php/jbms

ARTICLE

Optimization of the Mechanical Properties of Epoxy–Palm Fiber Composites Using a Simplex Experimental Design

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ABSTRACT

This article presents a study on the development of environmentally friendly materials. In the current context of environmental preservation, facing climate change and the search for material solutions, the development of ecological materials has become essential. Composites reinforced with natural fibers offer a sustainable alternative to synthetic materials. Among these fibers, palm fibers stand out for their low cost, lightness, and abundance. Derived from agricultural waste, they contribute to the valorization of local resources while reducing environmental impact. Their use promotes the development of high-performance and ecological composites. The objective of this study was to develop epoxy matrix composites reinforced with palm fibers. A simplex experimental design was used to vary the fiber concentration from 5% to 20%, while maintaining a constant resin/hardener ratio. The physical and mechanical properties were evaluated by tensile tests, viscosity analysis, and density measurements. The results indicate a continuous improvement in stiffness, with the Young's modulus increasing from 2 GPa to 3.67 GPa when the fiber content reached 20%. Tensile strength reached

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ARTICLE INFO
Received: 20 April 2026 | Revised: 7 May 2026 | Accepted: 29 June 2026 | Published Online: 17 July 2026
DOI: https://doi.org/10.30564/jbms.v8i3.13431

CITATION
Rakrouk, A., Lammari, L., Issami, I., et al., 2026. Optimization of the Mechanical Properties of Epoxy–Palm Fiber Composites Using a Simplex Experimental Design. Journal of Building Material Science. 8(3): 37–47. DOI: https://doi.org/10.30564/jbms.v8i3.13431

a maximum value of 62 MPa at a fiber content of 15%, before decreasing, suggesting an optimal concentration. This study confirms that palm fibers can serve as durable and effective reinforcements for optimized composite designs.

Keywords: Epoxy Composite; Palm Fiber; Simplex Experimental Design; Mechanical Properties; Young's Modulus; Tensile Strength

1. Introduction

At present, the materials sector is experiencing great difficulty achieving technological functionality and addressing environmental issues. Historically, the industry relied on synthetic materials, such as plastics or composites reinforced with glass and carbon fibers [1,2]. Synthetic materials are hailed as high-performing materials with excellent durability, and they have created many commercial opportunities throughout all sectors of the economy, including aeronautics and automotive industries [3,4]. Synthetic materials have been produced for many years with high levels of energy consumption, and the process of recycling synthetic materials at the end of their use is still complex and extremely inefficient. Synthetic materials' carbon footprint has also had a significant impact on climate change, making it a focal point for many contemporary environmental concerns [5]. With these facts now understood, scientific research and industrial development have begun to place a greater emphasis on the design and development of sustainable materials consistent with a broader vision of sustainable development [6]. This design includes the reduction of dependency on non-renewable resources [5,7], the substantial reduction in greenhouse gas emissions, and a decrease in the production of non-biodegradable waste [8–10].

In this dynamic context, composite materials, and more particularly biocomposites based on natural fibers, offer a balance between performance, cost, and respect for the environment [1]. These composites, intelligently combining two or more components with distinct properties, give a final material with synergistic properties often superior to those of each component taken individually [11]. The attractiveness of natural fibers as an alternative to synthetic fibers lies in their numerous intrinsic advantages: renewable and abundant, they are derived from agriculture or biomass, guaranteeing a sustainable resource; their low density contributes to the manufacture of lightweight materials, essential for reducing energy consumption in transport [12]. Among the available natural resources, palm fibers are of particular interest. Palm trees generate significant amounts of biomass in the form of leaves, petioles, and stems, which is often burned, contributing to air pollution and the waste of valuable resources [13]. Exploiting these lignocellulosic by-products as reinforcements for composite materials represents a double opportunity: environmentally, it transforms waste into a valuable resource, reducing combustion-related emissions and stimulating the local circular economy; economically, it valorizes the abundant local biomass, thus opening new economic sectors and generating income for local communities [14]. As with other natural-fiber composites, the performance of palm fiber-reinforced materials depends on multiple factors, primarily the mass percentage of incorporated fibers [15,16]. In terms of intrinsic mechanical performance, palm fibers compare favorably with other widely studied natural fibers. Reported single-fiber tensile strength values range from approximately 170 to 275 MPa for date palm fiber, compared with 320–800 MPa for jute, 350–700 MPa for sisal, and 500–900 MPa for flax; Young's modulus values are typically 2–12 GPa for date palm fiber, against 8–30 GPa for jute, 9–22 GPa for sisal, and 27–39 GPa for flax fiber [17,18]. While palm fiber therefore shows somewhat lower intrinsic stiffness and strength than flax, its mechanical properties remain comparable to those of jute and sisal, while offering the additional advantages of very low cost, local abundance in arid and semi-arid regions, and valorization of an agricultural by-product that would otherwise be discarded or burned. These characteristics make palm fibers prime candidates for the reinforcement of various polymer matrices, allowing the development of biocomposites suitable for numerous industrial and everyday applications [17,18]. Several recent studies have specifically investigated palm fiber-reinforced polymer composites. For instance, Ali [19] manufactured epoxy composites reinforced with date palm fibers at 5, 10, 15, and 20 wt% and reported a continuous increase in hardness with fiber content, together with changes in tensile behavior over the same range of fiber loadings used in the present study. More recently, Dhakal et al.[20] reviewed the use of date palm fibers as a sustainable reinforcement for bio-composites and concluded that, although the mechanical and thermal performance of these composites has been increasingly documented, systematic experimental designs capable of efficiently identifying the optimal fiber content while minimizing the number of trials remain scarce in the literature. This gap is particularly relevant for industrial applications, where minimizing experimental and material costs during formulation optimization is essential. The incorporation of natural fibers into a polymer matrix nevertheless remains a complex process whose success depends on multiple interconnected factors[21]. The final performance of the composite is influenced by the type of fibers and matrix, the surface treatments applied to the fibers, the manufacturing method and, above all, the size or mass percentage of the incorporated fibers. Insufficient addition of fibers will not achieve the desired reinforcement, as the matrix properties remain predominant in the composite[22]. There is therefore an optimal percentage of fibers for which the mechanical performance of the composite material reaches its maximum, before declining.

In this context, the main objective of the present study is to systematically and rigorously explore the influence of the variation of the mass percentage of palm fibers on the tensile mechanical properties of composites made with a given polymer matrix[23–25], using a Simplex experimental design to limit the number of required trials. More specifically, this research prepares several series of composite samples, each with a distinct mass content of palm fibers, which are then subjected to standardized tensile tests to precisely quantify the evolution of the breaking strength, Young's modulus (measure of stiffness), and the strain at break (measure of ductility) as a function of the proportion of fibers[24,26]. Detailed analysis of the results identifies the optimal percentage of palm fibers that provides the best tensile mechanical performance for the composite[27].

2. Materials and Methods

2.1. Theoretical Methods

Predicting the mechanical properties of composite materials, particularly those reinforced with short, randomly oriented particles or fibers, such as crushed palm waste, is essential for understanding material behavior and interpreting experimental results. These models enable the estimation of properties such as Young's modulus as a function of the composite composition. In addition to material characterization, manufacturing process optimization and resource management can be addressed using mathematical tools such as the Simplex method, providing a holistic perspective on the valorization of these biocomposites[28].

The Simplex Method for Process Optimization

Although this study focuses on characterizing composite mechanical properties, it is worth noting that mathematical optimization tools, such as the Simplex method, are essential for the transition from basic research to efficient industrial application. Simplex is a fundamental iterative algorithm in linear programming, designed to determine the optimal solution (profit maximization, cost minimization) to a problem formulated as a set of linear functions and constraints. A typical maximization problem, applicable to the production of these biocomposites, can be represented in the following standard form[28,29].

Maximize:

$$Z = c_1x_1 + c_2x_2 + \ldots + c_nx_n \tag{1}$$

Under constraints:

$$a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n \leq b_1$$

$$a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n \leq b_2$$

$$\ldots$$

$$a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n \leq b_m \tag{2}$$

$$x_j \geq 0, \quad \forall j = 1, \ldots, n \tag{3}$$

In this framework, Z in Equation (1) may represent the total profit, x_j the quantities to be produced of different types of composites (e.g., with varying fiber percentages), c_j the unit profits of each product[30], and the constraints $\leq b_i$ could symbolize the limits of available resources, such as the total quantity of crushed palm fiber (abundantly available from regions such as Tozeur, Tunisia), the quantity of resin, machine time, or labor.

The Simplex algorithm proceeds iteratively by moving from one feasible solution to another to another, improving the objective function at each step. The entering variable is selected based on the most negative coefficient in the objective function row of the Simplex table (for maximization), indicating the variable whose increase brings the greatest benefit. The output variable is then determined by the minimum ratio test, where $bp/a_{pj} = \min\{\frac{b_i}{a_{ji}}$ with $a_{ij} > 0\}$ is calculated, to ensure that the solution remains feasible[31]. The intersection of the chosen column and row defines the pivot element, around which row operations are performed to transform the table and advance towards the optimal solution.

Although not directly applied in the present material characterization study, this methodology may be useful and would be important for optimizing the production, logistics, and supply chain management of the composite materials developed in this study.

The indicative composition of the modified H132 epoxy hardener is presented in **Tables 1** and **2**, including aliphatic and cycloaliphatic polyamines, amine/epoxy adducts and reactive diluents, was carefully controlled to ensure efficient crosslinking and consistent matrix properties.

To ensure statistical reliability, each formulation was prepared in triplicate, and the reported values correspond to the average of the three measurements.

Table 1. Indicative chemical composition of the modified H132 epoxy hardener.

Component	Formulation Function	Presence (%)
Modified aliphatic polyamine	Primary Crosslinking Agent	60–85
Modified cycloaliphatic polyamine (optional)	Secondary Crosslinking Agent/Flexibility	0–10
Amine/epoxy adducts (amine modifiers)	Viscosity Reduction, Slight Lowering	5–20
Compatible plasticizers (e.g., glycerol, phthalate)	Fluidity, Workability	0–5
Nonylphenol-free reactive diluents (e.g., glycidyl ether, cresylglycidyl ether)	Reagents, Viscosity Adjustment	5–15
Miscellaneous additives (antifoam, stabilizers, pigments)	Chemical Stability	0–2
Nonylphenol	-	Absent
BDMA (2,4,6-tris(dimethylaminomethyl)phenol)	-	Absent

Table 2. General characteristics of the hardener components.

Component	Typical Chemical Formula	Main Role
Aliphatic polyamine	$(NH_2–CH_2–CH_2–)$*	Crosslinking
Cycloaliphatic polyamine	$C_{12}H_{24}N_2$ (e.g., IPDA)	Flexibility, chemical resistance
Glycidyl ether	$C_{13}H_{16}O_2$ (e.g., cresylglycidyl ether)	Viscosity reduction, modifier
Plasticizer	$C_3H_8O_3$ (glycerol)	Improves workability
Stabilizers		Anti-yellowing, preservation

Note: * represented as a generic repeating unit.

As summarized in **Table 2**, the chemical nature of each hardener component directly governs its functional role within the crosslinking process.

2.2. Experimental Methods

The lignocellulosic particles used as reinforcement in this study were obtained from date palm petioles collected in southern Tunisia. After collection and preliminary cleaning, the biomass was air-dried, mechanically ground, and sieved to obtain a controlled particle size distribution, ranging between 250 and 500 μm primarily. Additional drying in an oven at 45 °C for 24 h was performed to remove moisture, which is essential for good fiber-matrix adhesion. The average density of these particles is approximately 1.45 g/cm^3, as illustrated by the mixture preparation steps shown in **Figure 1**.

The polymer matrix consisted of a Bisphenol-A-based epoxy resin mixed with an H132 modified hardener at a resin-to-hardener mass ratio of 2:1. The density of the cured resin is 1.15 g/cm^3. The composites were manufactured using the open-mold casting technique (**Figure 2**), a simple and efficient technique for this type of material. A total of three series of samples were prepared, each with a variable mass ratio of crushed palm waste to the total mass of the composite: 0% (pure matrix), 5%, 10%, 15%, 20% and 25%. A detailed manufacturing protocol was rigorously followed to ensure sample homogeneity and reproducibility. First, the pre-dried crushed palm particles were weighed with an accuracy of ± 0.001 g, in accordance with the target mass ratios for each series. The required quantities of epoxy resin and hardener were accurately weighed and mechanically mixed using a mechanical stirrer for 3 min to ensure optimum homogeneity. The weighed palm particles were then gradually added to the resin and hardener mixture under continuous stirring for a further 5 min to promote optimum dispersion and reduce agglomeration.

Figure 1. Preparation of the composite mixture used for manufacturing the test specimens.

Figure 2. An open-mold casting procedure used for manufacturing the composite specimens.

The resulting composite mixture was gently poured into silicone molds, previously treated with a release agent to facilitate specimen extraction. These molds were specifically designed to produce dumbbell-type (Type I) tensile specimens, conforming to the dimensions required by ASTM D638 (165 mm long, 25 mm wide at the usable part and 2 to 3 mm nominal thickness). The filled molds were left to cure at room temperature for 24 h. A post-curing step was then carried out in an oven at 40 °C for 2 h, essential to ensure complete crosslinking of the matrix and to optimize the dimensional stability and mechanical properties of the composites. After demolding, the specimens were visually inspected and their edges were finely sanded to remove burrs and ensure precise geometry. Finally, the samples were conditioned at room temperature (23 ± 2 °C) and controlled relative humidity (50 ± 5%) for at least 48 h before being subjected to mechanical tests, in order to ensure their stabilization [32].

Mechanical Characterization

The tensile properties of the composites were evaluated using a universal testing machine (**Figure 3**). The tests were conducted in strict accordance with the international standard (Standard Test Method for Tensile Properties of Plastics).

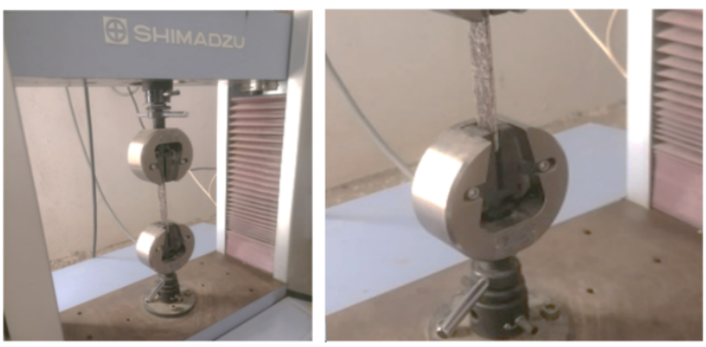

Figure 3. A tensile testing setup used for the evaluation of the mechanical properties of the composites.

A standardized testing protocol was adopted to ensure the reliability and comparability of the experimental results. At least one composition of each composite based on the pure matrix (0% fibers) five specimens were tested and this number was tested to get statistical importance and reduce the effect of variations present in composite materials. Before each test, the specimen was measured in terms of its important dimensions because these measurements are fundamental for accurate stress calculations. Specimens were immobilised between the composite jaws, making sure they aligned perfectly, etc to eliminate parasitic bending stress and sufficient clamping pressure to recover before it features slippage. The tests were carried out at a controlled room temperature (25 ± 2 °C) and at a constant crosshead speed of 5 mm/min. From these raw force-displacement data, the following fundamental mechanical properties were calculated for each specimen and statistically analyzed: Nominal Stress (σ), the applied force (F) divided by the cross-sectional area (A0) of the specimen (σ = F/A0); Nominal Strain, calculated as the elongation (ΔL); Young's Modulus (E), which represents the stiffness of the material and is determined by the slope of the linear elastic portion of the stress-strain curve; Stress at Break (σR), corresponding to the maximum stress that the specimen can withstand before breaking; and Strain at Break (ϵR), which is the strain associated with the breaking stress and provides an indication of the ductility of the material. Mean values and standard deviations were calculated for each series of composites to present statistically significant results and to assess the reproducibility of the tests.

2.3. Composite Formulation and Compliance Data

Maintaining this ratio is essential to ensure complete curing of the epoxy matrix and consistent mechanical performance of the epoxy matrix, which is essential for achieving reliable mechanical properties. As detailed in **Table 1**, the overall amount of epoxy phase (resin + hardener) was adjusted for each formulation, ensuring that only the reinforcement content (fibers) varied proportionally. The relative proportions of the chemical constituents within the epoxy phase remained constant. In addition, compliance with environmental and health standards was a priority, as evidenced by the absence of nonylphenol and BDMA in our formulations (**Table 3**).

Table 3. Environmental and regulatory compliance of the selected materials.

Criteria	Status
Nonylphenol-free	Compliant
BDMA-free	Compliant
REACH/ROHS compliant	Compliant
Low VOC emissions	Compliant

3. Results and Discussion

To optimize the formulation of the developed composites, a one-dimensional Simplex approach was employed. This approach is particularly useful for investigating the interactions between the constituents of a composite system, in this case, Palm Fiber and Epoxy Resin. Simplex allows for systematic variation of proportions and analysis of the impact of these variations on the properties of the final material, while minimizing the number of tests required. It allowed us to target the most promising formulations by identifying key relationships between composition and performance. The proportion of each component in the final composite is defined by Equation (4):

$$X_i = C_i / \sum C_i \tag{4}$$

where X_i represents the mass fraction of component i, and C_i is the quantity (mass or volume) of this component. In our case of a binary system of Fiber (F) and Epoxy Resin (E), this simplifies to Equation (5):

$$\text{Percentage of Fiber (F)} + \text{Percentage of Epoxy Resin (E)} = 100\% \tag{5}$$

Our formulations were systematically developed following this plan, the objective being to explore the influence of the fiber proportion on the final properties of the composite. A key parameter kept constant was the resin/hardener ratio (derived from Formulation 1 in **Table 4**)

The main properties measured for each composite formulation included tensile strength, Young's modulus, viscosity (at 25 °C), and density, viscosity of the uncured mixture (at 25 °C), and density of the cured composite. These indicators were chosen for their relevance in characterizing the mechanical performance and workability of the composites, with reference to the typical values presented in **Table 5**.

Table 4. Physico-mechanical properties of the developed composites.

Formulation	Date Palm Fiber (wt.%)	Epoxy Resin (wt.%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Viscosity (mPa·s)	Density (g/cm^3)
P1	5	95	25.3	2.00	350	1.15
P2	10	90	26.1	2.55	420	1.18
P3	15	85	27.3	3.10	500	1.21
P4	20	80	31.6	3.67	580	1.25

Note: All stress values are reported in MPa for consistency with international standards (1 N/mm^2 = 1 MPa).

Table 5. Typical physicochemical properties of the epoxy system.

Property	Typical Value	Unit
Viscosity (25 °C)	100–600	mPa·s
Density	1.00–1.05	g/cm^3
Amine value	400–900	mg KOH/g
Boiling point	>200	°C
Nonylphenol content	0	%
BDMA content	0	%

The percentages of Palm Fiber and Epoxy Resin in **Table 6** directly represent their mass proportions in the final composite, the sum of the two always being equal to 100%. This table presents the average results obtained for the key properties of our composites, depending on the Palm Fiber content. The Young's modulus values are those obtained during tensile tests.

As shown in **Table 6**, increasing the palm fiber content led to a progressive increase in composite density, Young's modulus, and tensile strength. The Young's modulus increased from 2.0 GPa for the 5 wt.% formulation to 3.67 GPa for the 20 wt.% formulation, indicating improved stiffness due to the reinforcing effect of the date palm fibers. Similarly, the tensile strength increased from 25.3 MPa to 31.6 MPa over the same fiber content range. These results suggest enhanced stress transfer between the epoxy matrix and the lignocellulosic reinforcement. The gradual increase in density, from 1.15 to 1.25 g/cm^3, remained within the typical range reported for natural-fiber-reinforced epoxy composites. Overall, the 20 wt.% fiber formulation exhibited the highest mechanical performance among the investigated compositions.

Table 6. Average physico-mechanical properties of the developed epoxy/date palm fiber composites.

Impact Point	Palm Fiber (F) (%)	Epoxy Resin (E) (%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Viscosity (mPa·s)	Density (g/cm^3)
P1	5	95	25.1	2.0	350	1.15
P2	10	90	26.3	2.55	420	1.18
P3	15	85	27.1	3.1	500	1.21
P4	20	80	31.6	3.67	580	1.25

These defects reduce the efficiency of stress transfer between the matrix and the fibers, creating weak points that decrease the overall strength of the material. This highlights the existence of an optimal fiber content to maximize tensile strength in this system, as shown in **Figure 4**. The viscosity of the uncured mixture increases significantly and continuously with the palm fiber content. Viscosity increased significantly from 350 to 580 mPa·s. This rise reflects the addition of solid matter, which increases internal friction and may require process adjustments for higher concentrations.

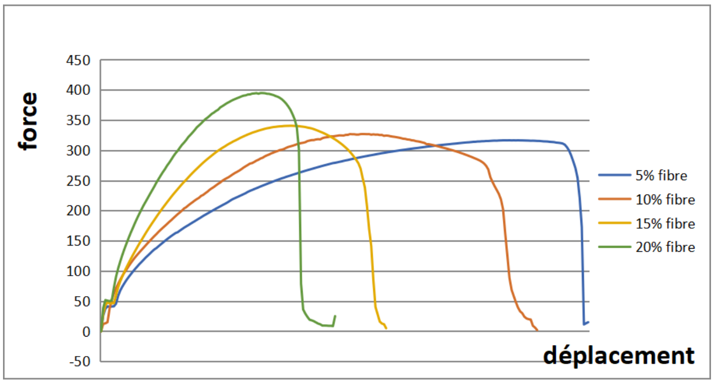

Figure 4. Influence of palm fiber content on the mechanical properties of composites (tensile strength and Young's modulus).

As shown in **Figure 5**, this increase is a direct consequence of the addition of solid matter (fibers) into the liquid matrix, which increases internal friction and impedes the flowability of the mixture. Although expected, this increase in viscosity has important implications for the processing of composites. Too high a viscosity can make the mixture difficult to handle, pour, or mold, potentially requiring adjustments to the processing conditions (e.g., increased temperature or pressure).

The density of the final composite also increases with the proportion of palm fibers. This trend (from 1.15 g/cm^3 to 1.25 g/cm^3) suggests that the density of palm fiber is higher than that of the pure epoxy matrix, or that its incorporation promotes better compaction of the material, thus reducing void volumes. Density is a key parameter for applications where the strength-to-weight ratio is an important design criterion (**Figure 6**).

This figure shows the evolution of density (in g/cm^3) as a function of the percentage of palm fibers (in %). An upward trend is expected.

Figure 5. Influence of palm fiber content on mixture viscosity.

Figure 6. Influence of palm fiber content on the density of composites.

4. Conclusion

This thorough investigation, utilizing a one-dimensional Simplex experimental design, allowed for a detailed assessment of how palm fibers impact the properties of epoxy composites. The findings underscore the intricate nature of optimizing formulations for these bio-based materials. The Simplex method was particularly useful, facilitating a structured exploration of the formulation landscape while minimizing the number of experimental trials needed. The results for fiber contents of 5%, 10%, 15%, and 20% emphasize the necessity of finding the right balance in reinforcement. Notably, the increase in Young's modulus from 2.0 GPa to 3.67 GPa demonstrates how palm fibers can significantly boost the stiffness of the composites, which is a key advantage for applications that demand high resistance to deformation. On the flip side, the analysis of tensile strength reveals a more nuanced picture. The peak tensile strength of 62 MPa was reached at a fiber content of 15%, but then it dropped at 20%. This trend suggests that once a certain threshold is crossed, the advantages of reinforcement might be compromised by challenges related to fiber distribution, resin saturation, or particle clumping. Additionally, the changes in mixture viscosity (ranging from 350 to 580 mPa·s) and composite density (from 1.15 to 1.25 g/cm^3) offer crucial insights for process engineering, highlighting the necessity to adjust manufacturing methods to accommodate increasingly complex flow behaviors. Beyond the impressive technical outcomes, this study reinforces the promise of palm fibers as a sustainable substitute for traditional synthetic reinforcements. The insights gained lay a robust scientific groundwork for developing predictive models and designing materials with customized properties.

Future research should focus on investigating surface treatments aimed at improving fiber–matrix adhesion, as well as on the integration of palm fibers into hybrid composite architectures. Such developments could open new opportunities for bio-based industrial applications and contribute to the advancement of a more circular and environmentally sustainable economy.

Author Contributions

Conceptualization: A.R. and L.L.; Methodology: A.R. and K.E.M.; Software: L.L. and I.I.; Validation: L.L. and K.E.M.; Formal Analysis: S.B.K. and R.N.; Investigation: A.R.; Resources: A.R.; Data Management: L.L. and A.R.; Drafting (First Version): A.R.; Drafting (Revision and Correction): L.L.; Visualization: I.I.; Supervision: A.R., L.L., I.I., S.B.K., K.E.M., and R.N.; Project Administration: A.R., L.L., I.I., S.B.K., K.E.M., and R.N. All authors have read and approved the final version of the manuscript.

Funding

This work did not receive any external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data is publicly available and presented in the article.

Conflicts of Interest

The authors declare that they have no conflict of interest.

AI Use Statement

During the preparation of this manuscript, the authors used Gemini solely for language refinement and grammatical formatting. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

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