Preliminary Assessment of Untreated *Encephalartos ituriensis* Fiber as Reinforcement in PLA-Based Biocomposites

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Abstract

This study explores the mechanical performance of poly(lactic acid) (PLA) biocomposites reinforced with natural fibers from *Encephalartos ituriensis* (E.I.), an underutilized tropical plant. Composite formulations containing 0, 5, 10, 15, and 20 wt% untreated E.I. fibers were melt-compounded using a twin-screw micro-compounder (Xplore MC 15 HT) and injection molded into ASTM D638-14 Type IV specimens for tensile testing. All tests were performed on a SHIMADZU AG-IC universal testing machine at 50 mm/min.

The results showed that incorporating E.I. fibers at up to 10 wt% (0010) maintained tensile strength values relatively close to the neat PLA group (0000) (63.3 ± 0.3 MPa), with a moderate peak at 5% (0005) (59.6 ± 1.5 MPa). At 10% fiber loading, strength dropped slightly to 56.2 ± 1.6 MPa. Beyond this threshold, a progressive decline in tensile strength was observed, reaching 54.5 ± 0.6 MPa at 15% (0015) and 48.4 ± 4.8 MPa at 20% (0020) content.

Conversely, the elastic modulus showed a steady increase with fiber addition, rising from 1227 ± 101 MPa for neat PLA to 1327 ± 44 MPa (5%), 1470 ± 17 MPa (10%), 1566 ± 39 MPa (15%), and peaking at 1660 ± 43 MPa for the 20% formulation, indicating improved stiffness with increasing reinforcement.

Elongation at break decreased progressively from 7.34 ± 0.85% at 0% fiber content to 5.71 ± 0.40% at 5%, 4.92 ± 0.07% at 10%, 4.35 ± 0.02% at 15%, and dropped further to 3.61 ± 0.57% at 20%, suggesting a reduction in ductility with higher fiber loadings.

These findings highlight the dual role of E.I. fibers: maintaining tensile strength at low loadings and enhancing modulus at higher ones. This supports their use as sustainable, high-modulus reinforcements in bio-based composites, with future work focusing on fiber treatment or hybrid designs.

Keywords: *Encephalartos ituriensis*, bio-composites, Poly(lactic acid) (PLA), natural fiber reinforcement, mechanical properties

Introduction

Bio-based polymer composites have gained strong momentum as industries seek materials that combine performance with lower environmental footprint and end-of-life flexibility. Among commercial biopolymers, poly(lactic acid) (PLA) stands out for its processability, biobased origin, and competitive baseline strength and stiffness relative to many commodity thermoplastics, albeit with limited toughness and heat resistance (Ç. Arslan et al., 2025; Kumar et al., 2021; Raj et al., 2023; Sanivada et al., 2020). Injection molding and twin-screw compounding are widely used, scalable routes for short-fiber PLA composites, enabling controlled fiber loading, dispersion, and part fidelity for mass-production applications (Ç. Arslan et al., 2025; Kumar et al., 2021; Rabbi et al., 2021; Sanivada et al., 2020).

Natural lignocellulosic fibers (e.g., flax, jute, sisal, coir, wood flour) are attractive PLA reinforcements due to low density, renewability, and favorable specific mechanical properties (Demir et al., 2025; Kumar et al., 2021; Raj et al., 2023; Sanivada et al., 2020). Across many PLA–natural fiber systems, a consistent trend emerges: as fiber content increases, tensile and flexural moduli tend to rise (stiffening), while tensile strength and ductility often decline beyond low–moderate loadings due to imperfect interfacial adhesion, fiber attrition, and voids/dispersion limits (Eselini et al., 2020; González-López et al., 2019; Guo et al., 2020; Jakab et al., 2025; Kumar et al., 2021; Narlıoğlu, 2022; Öncül & Sever, 2025; Soleimani et al., 2018). For instance, untreated wood-flour/PLA shows decreasing tensile

strength with increasing filler, while modulus increases—observed across compression-molded and 3D-printed routes with 5–20 wt% flour (Narlıoğlu, 2022). Injection-molded PLA with 10 wt% wood flour can achieve tensile strengths around ~50–60 MPa depending on molding parameters, underscoring the sensitivity of properties to processing even at fixed loading (Guo et al., 2020). With 10 wt% lignocellulose fibers, tensile strength typically drops relative to neat PLA if the interface is not engineered; annealing or crystallinity control can partially mitigate these losses while further increasing stiffness (Jakab et al., 2025). Similar stiffness-up/strength-down trade-offs are reported for other matrices (e.g., PP) filled with pruning-waste particles across 5–20 wt% (Öncül & Sever, 2025), reinforcing the generic nature of these mechanisms.

Interface quality is central. Reviews and targeted studies show that alkaline/silane/coupling-agent treatments, maleated compatibilizers, and chain extenders can improve stress transfer, reduce moisture uptake, and recover tensile/flexural strength at a given fiber fraction (Eselini et al., 2020; González-López et al., 2019; Harsanti et al., 2024; Jubinville et al., 2024; Kumar et al., 2021, 2024; Sanivada et al., 2020). For example, maleated or anhydride-based compatibilization in PLA/coir or PLA/PBAT–rice straw systems elevate modulus and, in many cases, partially restores strength versus untreated controls; however, elongation at break still tends to decline with increasing filler content (González-López et al., 2019; Jubinville et al., 2024). Even without compatibilizers, PLA reinforced with refined pulp fibers (TMP) can reach high stiffness and competitive tensile strength when fiber length/orientation and dispersion are preserved, highlighting the importance of micromechanics and processing-induced morphology (Tarrés et al., 2022). Conversely, when fiber bundles, poor wetting, or fines dominate, strength penalties appear at lower loadings, especially with untreated fibers (Eselini et al., 2020; González-López et al., 2019; Narlıoğlu, 2022; Soleimani et al., 2018).

In the Democratic Republic of Congo, where organic (~48%) and plastic (~26%) waste are major challenges, such biocomposites provide a sustainable valorization pathway (Diambu & Çevik, 2024). Within this landscape, *Encephalartos ituriensis* (E.I.) is an underexplored tropical fiber recently characterized with balanced composition (~48% cellulose, 23% hemicellulose, 23% lignin), moderate tensile strength (33.2 ± 7.8 MPa), and thermal stability up to ~296 °C (Diambu & Çevik, 2025), confirming its reinforcement potential. Building on this baseline, the present study evaluates for the first time the tensile behavior of untreated E.I.–PLA composites across 5–20 wt%. Establishing an untreated baseline is methodologically valuable for two reasons. First, it isolates the contribution of fiber addition and processing history from chemical coupling effects, clarifying the intrinsic reinforcement–ductility trade-off that must be managed in subsequent optimization (Kumar et al., 2021; Rabbi et al., 2021; Raj et al., 2023; Sanivada et al., 2020). Second, it provides a realistic comparator for industrial scenarios where chemical treatment may be constrained by cost, supply, or regulatory factors.

Accordingly, this work conducts a preliminary assessment of untreated E.I. fibers as reinforcement in PLA at 0, 5, 10, 15, and 20 wt%, using twin-screw micro-compounding and injection molding to produce ASTM D638-14 Type IV specimens for tensile testing. The design choices mirror common practice for short-fiber PLA systems (Guo et al., 2020; Kumar et al., 2021; Rabbi et al., 2021; Sanivada et al., 2020) and align with prior loading windows where stiffness gains are typically observed and strength plateaus/declines emerge (Eselini et al., 2020; González-López et al., 2019; Guo et al., 2020; Jakab et al., 2025; Komal et al., 2020; Kumar et al., 2021; Narlıoğlu, 2022). Based on literature precedents with untreated lignocellulosics, we hypothesize: (i) tensile modulus will increase monotonically with E.I. content; (ii) tensile strength will be retained at low loadings (≤10 wt%) but decline at higher fractions due to interfacial limitations; and (iii) elongation at break will decrease progressively with fiber content (Eselini et al., 2020; González-López et al., 2019; Guo et al., 2020; Jakab et al., 2025; Jubinville et al., 2024; Kumar et al., 2021; Narlıoğlu, 2022; Soleimani et al., 2018).

This study contributes three elements to the biocomposites literature:

1. It introduces E.I. fiber to the PLA composite domain and establishes untreated baselines across a practical 0–20 wt% window;
2. It maps the strength–stiffness–ductility trade-space under a single processing route (melt compounding + injection molding), facilitating direct comparison to extant untreated systems (wood flour, lignocellulose, coir, flax/jute) at matching loadings (Eselini et al., 2020; González-López et al., 2019; Guo et al., 2020; Jakab et al., 2025; Kumar et al., 2021; Narlıoğlu, 2022; Sanivada et al., 2020);
3. It frames future work on interface engineering (alkali/silane/coupling agents), crystallinity control (annealing), and hybridization (e.g., basalt or microfibrillated cellulose) using literature-quantified

improvements as targets (Eselini et al., 2020; González-López et al., 2019; Harsanti et al., 2024; Jakab et al., 2025; Jubinville et al., 2024; Kumar et al., 2021, 2024; Tarrés et al., 2022).

The results presented here strength retention at low loading, rising modulus with fiber content, and reduced ductility are consistent with the broader body of PLA–natural fiber findings, while providing the first quantitative reference for E.I.–PLA composites to guide subsequent treatment or hybrid-design studies (Eselini et al., 2020; González-López et al., 2019; Guo et al., 2020; Jakab et al., 2025; Jubinville et al., 2024; Kumar et al., 2021, 2024; Narlıoğlu, 2022; Rabbi et al., 2021; Raj et al., 2023; Sanivada et al., 2020; Soleimani et al., 2018; Tarrés et al., 2022).

Materials and Methods

Poly(lactic acid) (PLA, Luminy® L175, Total Corbion) was used as the matrix. L175 is an injection-grade PLA with high viscosity (L-isomer ≥99%), density of 1.24 g/cm³, melting temperature ~175 °C, and glass transition temperature 55–60 °C. The reinforcement was obtained from *Encephalartos ituriensis* (E.I.), a tropical species of the Zamiaceae family (Figure 1). Fibers were sourced from the Kisantu Botanic Garden (Democratic Republic of Congo), air-dried for one month, oven-dried at 60 °C for three days, ground, and sieved to <250 µm. Fibers were left untreated to provide a baseline for mechanical performance, consistent with prior studies reporting untreated natural-fiber composites [9,14,17,24].

Figure 1. *Encephalartos ituriensis* plant (source of fibers)

PLA and fibers were compounded using a twin-screw micro-extruder (Xplore MC 15 HT) at 200 °C, pelletized, and dried. The pellets were injection molded into ASTM D638 Type IV dog-bone specimens (Figure 2). All formulations were coded according to fiber content, as shown in Table 1.

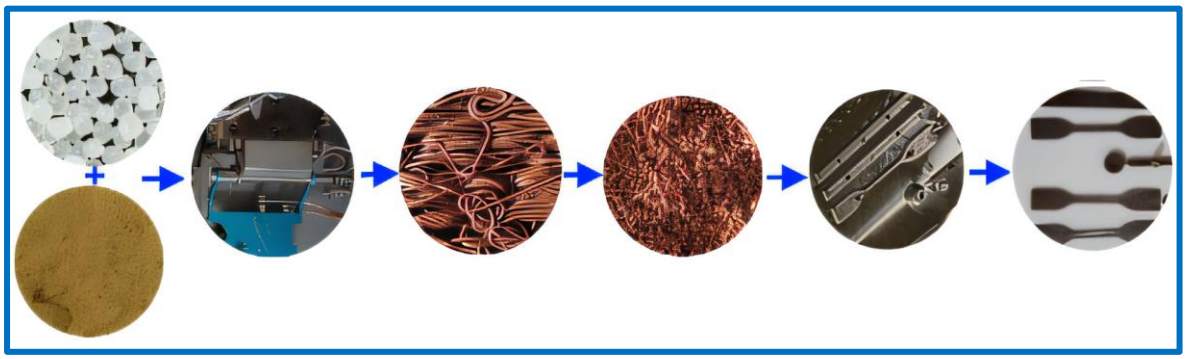

Figure 2. Schematic of PLA–E.I. composite preparation process: fiber drying → grinding and sieving (<250 µm) → compounding (200 °C, micro-extruder) → pelletizing → injection molding (ASTM D638 Type IV) → tensile testing

Tensile testing was carried out on a SHIMADZU AG-IC universal testing machine at room temperature and a crosshead speed of 50 mm/min in accordance with ASTM D638-14. For each composition, at least five specimens were tested. The values of tensile strength, modulus, and elongation at break were reported as mean ± standard deviation. Comparable approaches for PLA-based biocomposites have been adopted in earlier works [9,16,17,24].

Table 1. Formulations and sample codes for PLA–E.I. composites

Code	Fiber content (wt%)	Description
0000	0	Neat PLA (Luminy® L175)
0005	5	PLA + 5% E.I. fiber
0010	10	PLA + 10% E.I. fiber
0015	15	PLA + 15% E.I. fiber
0020	20	PLA + 20% E.I. fiber

Results and Discussion

Tensile response of PLA–E.I. biocomposites

Figure 3 shows that tensile strength is broadly retained at low fiber contents and then declines as loading rises. The neat PLA (0000) reached 63.3 ± 0.3 MPa; adding 5 wt% E.I. (0005) produced a modest decrease to 59.6 ± 1.5 MPa, while 10 wt% (0010) remained close at 56.2 ± 1.6 MPa. Beyond this threshold, strength dropped progressively to 54.5 ± 0.6 MPa (0015) and 48.4 ± 4.8 MPa (0020). This "strength plateaus at low loading then falls" pattern is consistent with many PLA–natural-fiber systems where interfacial adhesion limits stress transfer as fiber volume fraction and interfacial area increase (Demir et al., 2025; Eselini et al., 2020; González-López et al., 2019; Kumar et al., 2021; Narlıoğlu, 2022; Sanivada et al., 2020). For example, injection-molded PLA with 10 wt% wood flour reported 50–59.6 MPa depending on molding parameters (Guo et al., 2020), and unannealed 10 wt% lignocellulose–PLA showed ≈48–49 MPa (Jakab et al., 2025); our 10 wt% value (56.2 MPa) sits within this envelope. At 20 wt%, our 48.4 MPa compares favorably with several untreated 20 wt% references: abaca/PLA ≈42.1 MPa (untreated, IM) (Harsanti et al., 2024), PLA/PBS–flax 41.5–44 MPa (Ketata et al., 2022), and compression-molded wood-PLA 27.6 MPa (Narlıoğlu, 2022). Differences across studies reflect fiber species/geometry, processing route, and test rate; nonetheless, the trend of strength depression at higher contents is robust across untreated systems (Demir et al., 2025; González-López et al., 2019; Kumar et al., 2021; Sanivada et al., 2020).

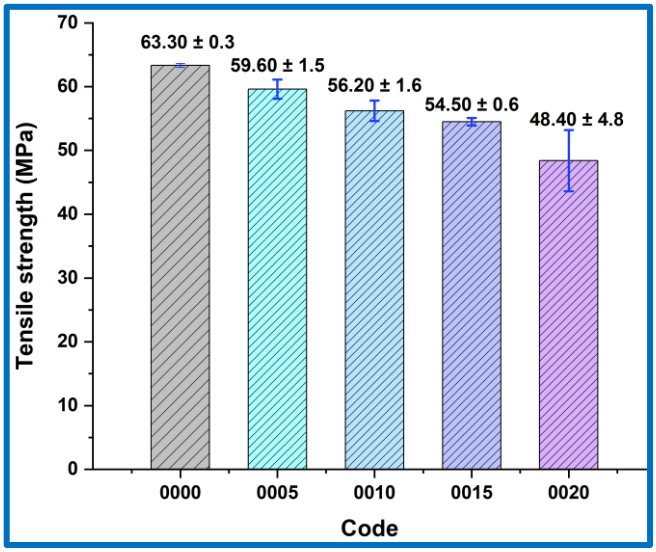

Figure 3. Tensile strength (MPa)

Stiffness enhancement with fiber loading

A monotonic increase in tensile modulus with E.I. content is evident in Figure 4: 1.227 ± 0.101 GPa (0000) → 1.327 ± 0.044 GPa (0005) → 1.470 ± 0.017 GPa (0010) → 1.566 ± 0.039 GPa (0015) → 1.660 ± 0.043 GPa (0020). This behavior mirrors the rule-of-mixtures expectation and extensive literature on PLA filled with lignocellulosics: modulus typically rises steadily as rigid fibers constrain

matrix deformation (C. Arslan & Dogan, 2019; Demir et al., 2025; Eselini et al., 2020; González-López et al., 2019; Jakab et al., 2025; Kumar et al., 2021; Öncül & Sever, 2025; Sanivada et al., 2020). The modulus increase with fiber content observed in this work is consistent with the crystallinity index (~64.9%) and microfibrillar structure reported for E.I. fibers (Diambu & Çevik, 2025), which support stiffness transfer even without interfacial treatments. For context, 20 wt% flax in an 80/20 PLA/PBS blend reached ≈4.2–4.35 GPa (Ketata et al., 2022); 10 wt% TMP fibers in PLA yielded ≈4.7 GPa (at 2 mm min^{-1}) (Tarrés et al., 2022); and untreated coir at 30 wt% increased flexural modulus versus neat PLA (González-López et al., 2019). Our more modest modulus slope is consistent with short, <250 µm E.I. particles and random orientation after micro-compounding/injection, which reduce the effective orientation factor (χ_1 ≈0.29–0.31 is typical for injection-molded short fibers (Tarrés et al., 2022)). The net result is a useful stiffness gain (≈35% from 0 to 20 wt%) without interfacial modification.

Ductility loss at higher E.I. contents

Elongation at break decreased from 7.34 ± 0.85 % (0000) to 5.71 ± 0.40 % (0005), 4.92 ± 0.07 % (0010), 4.35 ± 0.02 % (0015), and 3.61 ± 0.57 % (0020) (Figure 5). Such ductility loss is widely reported for PLA–natural-fiber composites and is attributed to fiber-induced stress concentrations, limited debonding/plastic flow in an unmodified interface, and moisture sensitivity of lignocellulose (C. Arslan & Dogan, 2019; Eselini et al., 2020; González-López et al., 2019; Jakab et al., 2025; Kumar et al., 2021; Öncül & Sever, 2025). Studies that improved interfaces via alkalization/silane/maleation (e.g., abaca with glutaraldehyde, or coir with maleated systems) commonly report better strength/strain retention at comparable loadings, underscoring that our untreated baseline leaves headroom for interface engineering (González-López et al., 2019; Harsanti et al., 2024; Kumar et al., 2024).

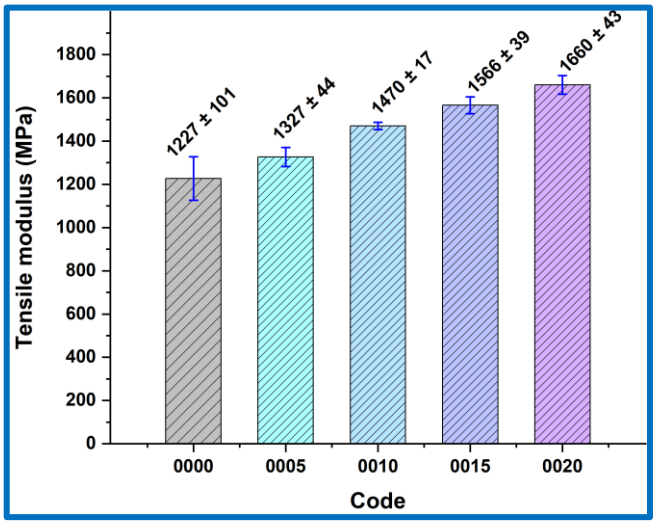

Figure 4. Tensile modulus (MPa)

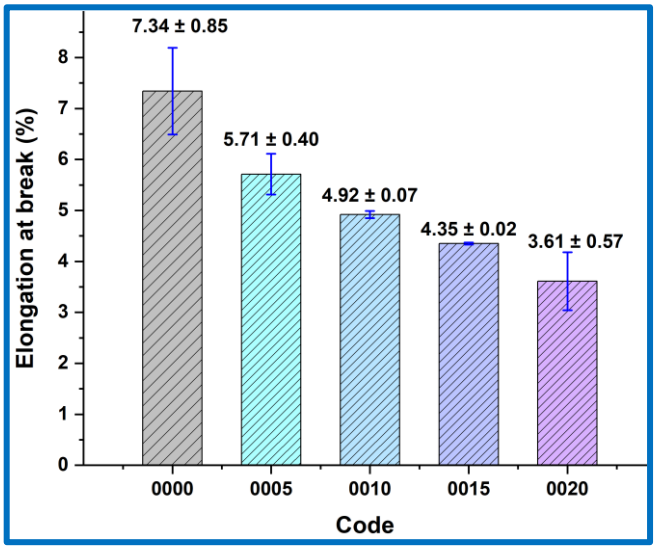

Figure 5. Elongation at break (%)

Influence of processing/test variables in the literature

Even at fixed fiber content, injection-molding parameters (melt temperature, injection speed, packing) can shift tensile strength by ~18% for 10 wt% wood-PLA (Guo et al., 2020). Similarly, annealing 10 wt% lignocellulose–PLA increased composite strength by ~4–7 MPa and modulus to ≈3.3–3.5 GPa (Jakab et al., 2025). Our data (ASTM D638-14, Type IV, 50 mm min^{-1}) therefore compare best to injection-molded, untreated systems at similar rates; higher moduli reported for some literature (e.g., TMP/PLA (Tarrés et al., 2022)) reflect longer fibers, higher aspect ratios, and different testing speeds/specimens.

Practical implications and next steps

At ≤10 wt% E.I., strength retention is acceptable while stiffness rises; at ≥15 wt%, modulus gains continue but strength and ductility fall more sharply. This trade-off is typical of untreated PLA–fiber systems and suggests two straightforward routes for improvement: (i) interfacial modification (alkali/silane or reactive coupling) to mitigate strength losses and moisture effects (González-López et al., 2019; Harsanti et al., 2024; Kumar et al., 2024), and (ii) process optimization/annealing to tune crystallinity and reduce property scatter (Guo et al., 2020; Jakab et al., 2025; Komal et al., 2020). Hybridization with a small fraction of high-modulus inorganic fibers (e.g., basalt) is another option to raise stiffness without excessive natural-fiber loading (Eselini et al., 2020; Finnerty et al., 2023).

Table 2. Comparative tensile properties of PLA-based composites near matching fiber contents (injection-molded unless stated)

Study / System	Fiber treatment	Filler (wt%)	σ_t (MPa)	E_t (GPa)	ε_b (%)	Ref.
This work (Luminy L175-E.I.)	Untreated	5	59.6 ± 1.5	1.327	5.71	–
This work (Luminy L175-E.I.)	Untreated	10	56.2 ± 1.6	1.470	4.92	–
This work (Luminy L175-E.I.)	Untreated	20	48.4 ± 4.8	1.660	3.61	–
PLA- wood flour	Untreated	10	50.4–59.6	n/a	n/a	(Guo et al., 2020)
PLA-lignocellulose	Untreated	10	48–49	~3.1	n/a	(Jakab et al., 2025)
PLA-abaca	Untreated	20	42.1	n/a	n/a	(Harsanti et al., 2024)
PLA-PBS (80/20) / flax	Untreated	20	41.5–44.0	4.16–4.35	2.4–3.8	(Ketata et al., 2022)
PLA-wood flour (CM)	Untreated	20	27.6	2.64	n/a	(Demir et al., 2025)
PLA-TMP fibers	No compatibilizer	10	63.4 ± 1.3	4.7 ± 0.2	3.2 ± 0.2	(Tarrés et al., 2022)
PLA-basalt fiber	Untreated BF	10	83.8 (1×)	3.18	3.72	(Finnerty et al., 2023)

Cross-study synthesis

- **Strength:** Our 10 wt% result aligns with other untreated 10 wt% systems ((Guo et al., 2020; Jakab et al., 2025)) and exceeds some particle-filled baselines at 20 wt% ((Harsanti et al., 2024; Ketata et al., 2022; Narlıoğlu, 2022)).
- **Modulus:** As expected for short, randomly oriented fibers, our modulus gain is moderate but monotonic; higher absolute moduli reported elsewhere typically involve longer fibers, higher aspect ratio, alignment, or different matrices/conditions ((González-López et al., 2019; Ketata et al., 2022; Tarrés et al., 2022)).
- **Ductility:** The drop in εb with E.I. loading mirrors the consensus for untreated PLA–fiber composites ((Eselini et al., 2020; González-López et al., 2019; Jakab et al., 2025; Kumar et al., 2021; Narlıoğlu, 2022)).

Overall, Figures 3–5 demonstrate that untreated E.I. fibers provide useful stiffness reinforcement at 5–20 wt% with acceptable strength retention up to ~10 wt%, while higher loadings incur the usual strength/ductility penalties observed across untreated PLA–natural-fiber literature. Strategic interfacial modification and processing optimization identified in prior work offer clear pathways to push the

strength–stiffness envelope in future iterations (González-López et al., 2019; Harsanti et al., 2024; Jakab et al., 2025; Komal et al., 2020; Kumar et al., 2024; Rathore et al., 2022).

Conclusion

This preliminary study evaluated the mechanical behavior of poly(lactic acid) (PLA, Luminy® L175) reinforced with untreated *Encephalartos ituriensis* (E.I.) fibers at 0–20 wt% loading. The results showed that tensile strength was largely retained up to 10 wt% (56–60 MPa, close to neat PLA at 63 MPa) but declined at higher fiber fractions (≈48 MPa at 20 wt%). Conversely, tensile modulus increased steadily with fiber content, rising by ~35% at 20 wt% (1.66 GPa), while elongation at break decreased progressively (7.3% → 3.6%). These findings confirm that E.I. fibers, even in untreated form, can serve as sustainable stiffening reinforcements for PLA, with acceptable strength retention at low to moderate loadings. The trade-off between modulus gain and ductility loss mirrors well-established trends in other untreated natural fiber–PLA systems, validating the consistency of the present results. Future work should therefore focus on interfacial modification (alkali/silane or reactive compatibilizers) and processing optimization to improve stress transfer and mitigate ductility losses at higher fiber contents. This study provides the first baseline dataset for PLA/E.I. biocomposites, demonstrating both their promise as renewable reinforcement systems and the opportunities for property enhancement through tailored interface engineering.

Acknowledgement

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