

Innovations in sustainable additive manufacturing: PLA, Amazon wood waste, Brazil nut oil

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Abstract

Responding to the growing interest in lignocellulosic materials for 3D printing, this research addresses the need for sustainable solutions, employing Amazonian wood waste and Brazil nut oil (BNO) as a natural binder for polylactic acid (PLA). We successfully developed filaments from a composition of 4% powdered sawdust of *Nectandra rubra* and *Zygia racemosa*, respectively with medium and high density, with 91% PLA and 5% BNO, which were extruded and printed. Physical-mechanical and characterization tests were performed using SEM, TGA, and FTIR. The incorporation of wood increased flexural strength, but reduced compression and tensile strength. FTIR analysis showed compatibility between the components, although the addition of wood caused agglomeration as indicated by SEM. The high-density species increased the thermal stability, as indicated by TGA. This study confirms the potential of filament developed with Amazonian woods and BNO, opening new avenues for sustainable additive manufacturing.

Keywords: 3D printing, biocomposite, extrusion, polymers, vegetable oil.

Data Availability: All data supporting the findings of this study are available from the corresponding author upon request

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1. Introduction

Among the various 3D printing techniques, also known as Additive Manufacturing (AM), Fused Deposition Modeling (FDM) stands out. FDM involves the extrusion of a thermoplastic filament, which is melted and precisely deposited, layer by layer, onto a platform^[1,2]. This technique has several applications in sectors such as automotive, aeronautical, construction, culinary arts, clothing, and medical engineering^[3-6]. PLA (polylactic acid) biopolymer is one of the most widely used in FDM, derived from corn starch or sugarcane, and stands out for its biodegradability, non-toxicity, and biocompatibility. It is processed industrially by extrusion or injection molding. The mechanical and thermal properties, ease of molding, and print quality of PLA are some of the characteristics that make it attractive for use compared to petroleum-derived plastics^[1,7].

PLA mixed with wood powder and synthetic or natural binders has the potential to form composites and transform them into filaments using extruders^[3]. Studies show the use of PLA as a matrix in combination with wood as reinforcement^[7-10] in the manufacture of filaments for 3D printing. Despite these advances, there is a notable gap in

the application of this technique with Amazonian tropical woods from forest management areas. In sawmills in the Brazilian Amazon, wood waste can represent about 60 to 70% of industrialized logs processing^[11-13]. Furthermore, there are few studies on the use of wood waste in AM, however, the reuse of wood waste in polymeric matrices is promising for AM^[2].

Some works indicate applications in 3D printing of wood species in combination with polymers, adhesives, plaster, cellulose, cement, lignin, sodium silicate, maleic anhydride, epoxy resin, polyurethane, vinyl acetate, among others^[3]. Therefore, it is noted that mostly non-biodegradable and even toxic substances are used to manufacture filaments, as well as the absence of vegetable oil binder in additive manufacturing.

For the manufacture of a biocomposite, the addition of a binding agent is necessary to improve the adhesion between the wood incorporated into the PLA^[9,10]. In turn, natural Brazil nut oil, *Bertholletia excelsa*, (BNO) has the potential to act as a binding agent between sawdust and PLA, promoting a more homogeneous filament, since it was used for the first time as a natural binder in 3D printing

in this research.. BNO is a regional raw material from the Amazon, biodegradable, non-toxic and has antioxidant, plasticizing and lubricating properties^[14]. In addition, this oil is applied as a biofuel and in the food, cosmetic and pharmaceutical industries^[14-16].

Studies show satisfactory technological characteristics of wood/PLA in AM. Ramaux et al.^[2] show that the wood species and particle size affect the properties of the printing composite. Narlioğlu et al.^[17] concluded that the addition of *Pinus nigra* (medium density) sawdust in a proportion of 0–20% to PLA, made in a twin-screw extruder, reduced tensile strength and increased flexural strength, acting as an adequate and sustainable reinforcement for high-quality 3D filaments. Tao et al.^[10] extruded PLA and 5% of 14 µm *Aspen* wood sawdust (low density) in a PLA matrix using a single-screw extruder and identified that the addition of wood increased flexural strength but reduced tensile strength, with a decrease in thermal stability with the addition of wood. Some works^[18,19] with commercial filament of 40% wood fiber and 60% PLA showed that printing speed affects appearance, density and compression strength, while tensile and flexural strength are little influenced; however, these properties decrease with increasing extrusion temperature due to thermal degradation of the fibers.

So, this research aims to investigate the feasibility of composite manufacturing from powdered wood waste of Amazonian species, in combination with virgin PLA pellets, and the addition of BNO, in order to develop a sustainable filament for application in 3D printing.

2. Materials and Methods

2.1 Materials

The wood waste used in this study was sourced from Precious Woods (*Mil Madeiras*), a forest management company located in Itacoatiara, Amazonas, Brazil, and certified by the Forest Stewardship Council (FSC). Initially, the length, width, and thickness of the sawmill's mechanical processing waste were measured using a tape measure to quantify its volume (Figure 1a). Subsequently, in the band saw machinery (Figure 1b), test specimens were cut from the collected waste in an oriented manner in the planes (transverse, tangential and radial) in dimensions of 2 cm x 2 cm x 2 cm (Figure 1c). The samples were sent for wood identification, confirming the species *Zygia racemosa* (Angelim rajado), family *Fabaceae*, density of 0.95 to 1.00 g/cm³ (high) and the species *Nectrandra rubra* (Louro gamela), family *Lauraceae*, density of 0.65 g/cm³ (medium).



Figure 1. Steps taken from obtaining the residues to the granulometry of the species.

The volume of wood residues was approximately 7050 cm³ and 10816 cm³ for *Z. racemosa* and *N. rubra*, respectively.

Subsequently, the wood waste was processed into shavings using planer-trowel equipment (Figure 1d) to facilitate grinding in an ACB Labor brand rotary knife mill, yielding sawdust (Figure 1e). The sawdust of each species was sieved through 150 µm openings, obtaining the sawdust powder (Figure 1f). The PLA pellets in natural color are from the North American company NatureWorks, imported by the Brazilian company 3D LAB. PLA has a melting temperature of 165°C - 180°C, glass transition (T_g) of 55°C - 65°C and density of 1.24 g/cm³. Each distinct formulation (in %wt) was assigned a specific nomenclature, being: 1 (PLA 100%); formulation 1: *N. rubra* (4% sawdust, 91% PLA and 5% BNO); formulation 2: *Z. racemosa* (4% sawdust, 91% PLA and 5% BNO).

2.2 Methods

2.2.1 Extrusion

Before each extrusion, the PLA pellets were dried at 90 °C for 2 hours and sawdust were dried at 103 °C for 24 hours (Figure 2). The BNO with 5% was manually mixed with 91% of pellets and 4% of sawdust powder (150 µm). These formulated proportions proved to have no impact on 3D printing, as they did not clog the 3D printer. The formulation was fed into the extruder, where the mixture was detailed by the single-screw extruder and melted in the heater, exiting through the nozzle as a ±1.75 mm filament, which received a thermal shock from the fan and was manually wound. During the extrusions, adjustments to the screw speed and extruder temperature were necessary when the filament became too soft or had incompletely fused parts, causing losses. The extrusion temperatures of the PLA pellets ranged between 285 °C and 290 °C. The species *Z. racemosa* presented greater manufacturing difficulty during extrusion, as the filaments broke more frequently compared to *N. rubra*, ranging from 300 °C to 295 °C for *Z. racemosa* and from 295 °C to 290 °C for *N. rubra*. The high temperature required can be explained by the equipment not being robust at the industrial level, as well as the composition of species may have been affected,

with the species (*Z. racemosa*) having thick fibers, more closed ducts and high density^[20] requiring a higher extrusion temperature. On the other hand, the ease of extrusion of *N. rubra* can be explained by the thin to medium-walled fibers and more open pores, being an easy-to-work wood^[21]. In PLA extrusion, the pellets were extruded at a temperature of 290 °C and screw rotation speeds ranging from 8.42 rpm to 25.10 rpm to adjust the filament diameter as close as possible to 1.75 mm.

2.2.2 3D printing of samples by FDM

3D objects were graphically modeled using Ultimaker Cura software in order to 3D printer could receive commands and print the objects. Filaments with a composition of 4% sawdust, 5% BNO, and 91% PLA (for both species) were printed using a Creality Ender 3 3D printer (Figure 3a), using the FDM method, following 3D printing parameters. During 3D printing (Figure 3b), the filament passes through a heating block attached to the printer at a temperature of 200°C that melts it and is transferred to a nozzle with a diameter of 0.4 mm, at a printing speed of 50 mm/s, with a ±45° raster angle, and deposits the extruded material layer by layer of 0.2 mm (except the first layer, which is 0.4 mm) on top of a hot platform with a temperature of 60°C that moves during printing in the x, y and z directions until forming the object with 100% filled. Figures 3c, 3d, 3e show the printed samples for the mechanical, physical and characterization tests for each formulation.

2.3 Physical properties

Printed samples measuring 36 mm x 12.5 mm x 6 mm were used in all physical tests. Apparent density of these samples were obtained by measuring the mass on an analytical balance and measuring the volume (length, width and thickness) using a digital caliper and specimeter, and calculating the mass and volume ratio using Equation 1:

$$D = M / V \quad (1)$$

where: D: density (g/cm³); M: mass (g); V: volume (cm³).

Absorption and swelling were determined by ASTM 1037. Test specimens were measured in mass and volume

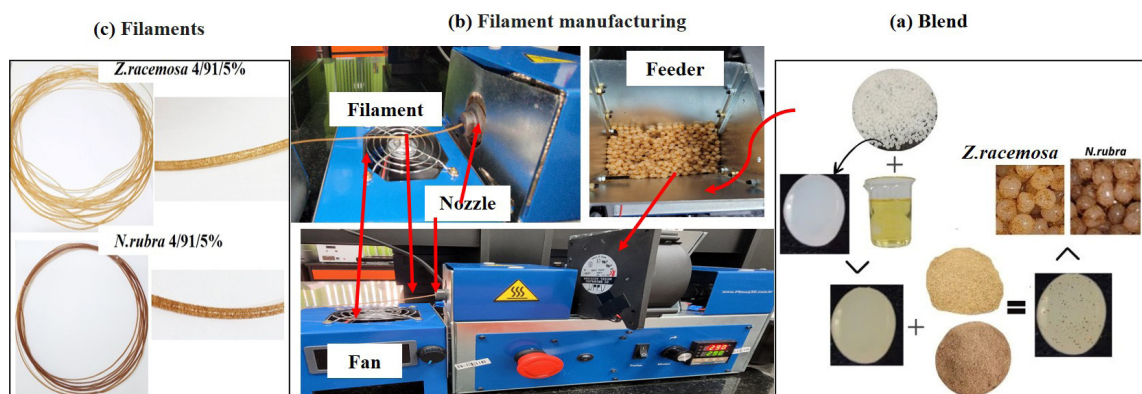


Figure 2. Steps to develop filament: (a) preparation of mixtures; (b) equipment used: extruder with temperature panel and feeder, external fan; (c) filaments.

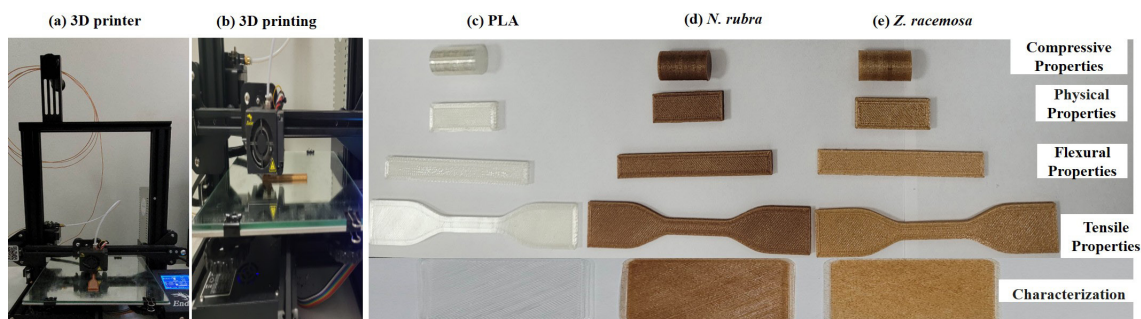


Figure 3. (a) 3D printer. (b) 3D printing and (c), (d), (e) printed test specimens.

before and after immersion in distilled water for 2 hours, plus an additional period of 22 hours (total of 24 hours), with removal of excess water from the sample on filter paper. The values of thickness swelling were obtained according to Equation 2:

$$Ts = \left(\frac{T1 - T0}{T0} \right) \times 100 \quad (2)$$

where, Ts: thickness swelling of the test specimen (%); T1: thickness of the test specimen after immersion (mm); T0: thickness of the test specimen before immersion (mm).

The water absorption were obtained according to Equation 3:

$$Wa = \left(\frac{M1 - M0}{M0} \right) \times 100 \quad (3)$$

where, Wa: water absorption (%); M1: mass of the test specimen after immersion (g); M0: mass of the test specimen prior to immersion (g).

The moisture content of the filaments and printed parts (or samples) were obtained on Shimadzu's MOC63 moisture determination scale, with calibration at 50°C for 15 minutes, presenting the moisture value in percentage and a margin of error of 0.1%.

2.4 Mechanical properties

The tensile test was followed in accordance with the ASTM D638 standard on samples with dimensions of 114.3 mm x 19.5 mm x 4.064 mm, with application of the type IV test, using a speed of 5 mm/min, a span of 50 mm and a load cell of 2 kN in the Instron machine, model 5564 and determining the tensile strength (TS) and the tensile modulus (TM). In the compression test, the ASTM D695 standard was used. Samples with dimensions of 12.7 mm x 12.7 mm x 25.4 mm were tested in the vertical direction at a speed of 1.3 mm/min and a load cell of 100 kN in the Instron machine, model EMIC 2300 and obtaining the compressive strength (CS) and the compressive modulus (CM). In the flexural test, the ASTM D790 standard was used to determine the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) with a 2 kN load cell on the Instron machine, model 5564. Test specimens with rectangular dimensions of 80 mm x 10 mm x 4 mm were tested and

supported in a 57 mm span to receive the application of a concentrated load in the middle of the sample at a speed of 1.53 mm/min.

2.5 Scanning Electron Microscopy (SEM) Test

Printed samples were metallized with a thin layer of gold to enhance electron conductivity, and morphological images of their surface structures were generated using a JSM IT500 HR microscope.

2.6 Thermogravimetric Analysis (TGA)

We observed the stages of thermal degradation (mass loss) of the printed samples with masses around 11 mg in the Shimadzu TGA-50 thermal analyzer, starting the process by heating at a rate of 10°C/min until reaching a temperature of 500°C.

2.7 Fourier Transform Infrared (FTIR) Spectroscopy

Functional groups and chemical bonds in the printed samples and sawdust powder from both species were analyzed via Fourier Transform Infrared (FTIR) Spectroscopy using the Attenuated Total Reflectance (ATR) technique. Measurements were performed on an Agilent Technologies Cary 630 instrument in the range of 4000 to 650 cm⁻¹ with 128 scans.

2.8 Statistical analysis

We used the OriginPro 2023b and R Studio programs. We performed Analysis of Variance (ANOVA) with Tukey's test, with $p < 0.05$ significant for PLA and the formulations of *N.rubra* and *Z.racemosa* with 5 repetitions of the physical test, totaling 15 samples. 5 repetitions were used for each mechanical test, totaling 45 samples. The characterization was analyzed based on the observations of the graphs generated from 1 sample of each formulation.

3. Results and Discussions

3.1 Filament diameters

The diameters for PLA filaments comprised a frequency around 1.65 ± 10 mm. The species *N.rubra* obtained diameters between 1.55 mm and 1.70 mm. *Z.racemosa* obtained a frequency of diameter of 1.60 ± 10 mm. Despite the variations in diameters, it was possible to print the 3D parts.

3.2 Physical properties

The PLA presented a density of 0.842 g/cm³ in Table 1, which was lower than that found in the theoretical density between 1.23 and 1.24 g/cm³[22]. The density 0.96 g/cm³ of *N.rubra* of the printed part was the highest among the formulations, since the sawdust powder added to the PLA contributed to this increase, being significant between formulations. The printed part of *Z. racemosa* presented a density of 0.845 g/cm³, which suggests that the difficulty in extruding this species and the variations in filament diameters may have consequences in not increasing density as observed for *N.rubra*. For comparison purposes, the commercial filament of 40% wood fibers and 60% PLA has a density of 1.20 g/cm³, changing values with increasing printing speed with speeds of 30, 50 and 70 mm/s and densities of 1.06, 1.02 and 1.0 g/cm³, respectively[18]. The quality and mechanical properties of FDM-printed components are influenced by density and several printing parameters[19]. Therefore, density plays an important role in material performance, as it will be influenced by voids, weight, printing defects, extrusion quality, among others.

The moisture content of the filaments and 3D printed parts was low and not significant. PLA had the highest moisture content of the filaments at 1.07%, followed by *Z.racemosa* with 0.96% and 0.72% for *N.rubra* (Table 1). The moisture content of the printed parts was similar between formulations, showing that moisture content decreased after 3D printing. Drying the pellets and sawdust powder

before extrusion may have contributed to a material with low moisture content, as well as storing the pellets to avoid absorbing moisture and the printed parts in airtight bags with silica. The moisture content results from printed parts are below when compared to those in the literature. According to Yang[19], moisture content of 2.1% and 1.9% was obtained for samples printed with PLA and *Cedrela* spp. at 200°C and 210°C, respectively, and no significant differences were observed. Wood parts printed with PLA subjected to a temperature of 20°C and relative humidity (RH) of 33%, 65% and 85% increased from 0.8 to 1.6%, 1.4 to 3% and 2 to 4%, respectively[10].

The printed parts of PLA and *Z.racemosa* absorbed more water and swelled in thickness compared to *N.rubra*. However, the results shown in Table 2 did not show significant differences in absorption and swelling of the printed samples after 2 h and 24 h, evidencing that the biocomposite parts of the Amazonian species studied can swell and shrink in thickness and absorb water in a similar way to PLA parts.

3.3 Mechanical properties

The results of the tensile, compression, and flexural tests of the printed samples are shown in Table 3. In tensile testing, PLA showed higher TS and TM values among the formulations; however, PLA had a lower TS when compared to the literature, since tensile in other works strength is approximately 50 to 70 MPa[22] and 44.2 MPa[19]. It also had a lower TM when compared to the value reported in the PLA pellet manufacturer's DataSheet, which is around 1896 MPa.

Table 1. ANOVA results of density, moisture of filaments and printed samples.

Formulations	Density*(g/cm ³)	Filament moisture*(%)	Moisture printed samples*(%)
PLA	0.842 ± 0.053 b	1.07 ± 0.608 a	0.41 ± 0.06 a
Nr/OCB	0.96 ± 0.058 a	0.72 ± 0.388 a	0.32 ± 0.108 a
Zr/OCB	0.846 ± 0.059 b	0.96 ± 0.288 a	0.31 ± 0.117 a

*Values are mean ± standard deviation (S) with (n = 5). Same letter in each column is not statistically different at a significance level of p < 0.05 between formulations according to the Tukey test.

Table 2. ANOVA results of each absorption and thickness swelling formulations.

Formulations	Water Absorption (Wa)*		Thickness Swelling (Ts)*	
	2 h	24 h	2 h	24 h
PLA	3.06 ± 1.16 a	5.67 ± 3.01 a	0.10 ± 0.164 a	0.15 ± 0.030 a
<i>N.rubra</i>	2.10 ± 0.439 a	4.87 ± 2.44 a	0.03 ± 0.020 a	0.09 ± 0.053 a
<i>Z.racemosa</i>	3.77 ± 0.14 a	7.94 ± 1.48 a	0.06 ± 0.062 a	0.11 ± 0.065 a

*Values are mean ± standard deviation (S) with (n = 5). Same letter in each column is not statistically different at a significance level of p < 0.05 between formulations according to the Tukey test.

Table 3. ANOVA results for each mechanical test formulations.

Formulations	Tensile Properties*		Compression Properties*		Flexural Properties*	
	TS (MPa)	TM (MPa)	CS (MPa)	CM (MPa)	MOR (MPa)	MOE (MPa)
PLA	12.2 ± 1.30 a	794 ± 65 a	28.09 ± 13.7 a	793.66 ± 312 a	33.97 ± 18.3 a	963.59 ± 388 b
<i>N.rubra</i>	7.56 ± 1.90 b	407 ± 320 b	17.23 ± 4.25 a	503.54 ± 145 ab	34.4 ± 4.09 a	1478.28 ± 78.8 a
<i>Z.racemosa</i>	7.76 ± 1.60 b	687 ± 133 ab	12.34 ± 8.53 a	298.26 ± 96 b	38.58 ± 6.75 a	1496.84 ± 131 a

*Values are mean ± standard deviation (S) with (n = 5). Same letter in each column is not statistically different at a significance level of p < 0.05 between formulations according to the Tukey test.

This aspect may be associated with the void in the samples and the oscillations in the diameters of the filaments that feed the samples during 3D printing with less or more material, in addition to the high temperature used in the extruder at the laboratory level causing thermal degradation. Similar behavior was observed by Agaliotis et al.^[23], in which the TS was lower than the value reported by the manufacturer, which was attributed to the void in the part.

Wood formulations showed lower TS and TM than PLA, which may be associated with the lack of long fibers in the wood, making them less resistant when force is applied in opposite directions. In the study by Yang and Yeh^[18], the TS of the wood/PLA filament with contents of 30, 50 and 70% ranged from 19.2 MPa to 19.8 MPa and the TM from 1650 MPa to 1731 MPa. Most PLA tensile samples and species broke in the transverse direction (Figure 4).

In compression, we noted that CS of the wood formulations was lower than PLA, although not significantly so. For CM, the values of the species were lower than those of PLA, however, with a significant difference between *Z. racemosa* and PLA. The voids caused by the variation in filament diameter as well as the low density caused delamination of the parts in the form of lines in both the wood formulations and PLA (Figure 4), as the compressive load was applied. In the literature, Agaliotis et al.^[23] found mechanical reduction due to the formation of voids between the layers and the reduction in molecular weight due to extrusion and printing.

Regarding flexural tests, Table 3 shows that addition of wood increased the elastic capacity of 3D parts. The MOE values of *N. rubra* and *Z. racemosa* was 153% and 155% higher than PLA, respectively, with a significant difference compared to PLA. The MOR values did not show a significant difference, highlighting that *Z. racemosa* presented a

higher MOR among the formulations. The results of the formulations with wood in this research are close to the commercial wood/PLA filament found by Yang and Yeh^[18] (32.3 to 34 MPa), but slightly lower in MOE (1575 to 1680 MPa). Furthermore, the samples with wood showed more prominent bending, corroborating the elastic capacity of the material (Figure 4).

Agglomerations resulting from the addition of wood in the printed layers, visualized in SEM, indicate a weak interface according to Tao et al.^[10], which may have affected the mechanical properties. Also, thermal degradation may have influenced the mechanical properties due to the high temperatures used in the extruder to manufacture the filaments, as well as variations in diameters that caused voids in the filler layers. Furthermore, the mechanical properties are strongly dependent on the printing orientation (0°, 45° and 90°) due to anisotropy, and in this research a $\pm 45^\circ$ angle was used.

The filament manufacturing process in large industrial extruders with automated temperatures and speeds may reduce the need for adjustments during filament production and allow for the use of lower temperatures and more homogeneous filaments.

3.4 Scanning Electron Microscopy (SEM) Test

We verified the morphology of the composites through the microstructure of the printed parts. In the PLA part, we identified pieces that were not completely fused, as shown in Figure 5a. In Figure 5b of *N. rubra* and Figure 5c of *Z. racemosa*, we verified agglomerations of pellet pieces with wood powder and a more uniform printing layer of *N. rubra*. However, it was possible to print the parts with potential for use, showing that the granulometry and amount of wood

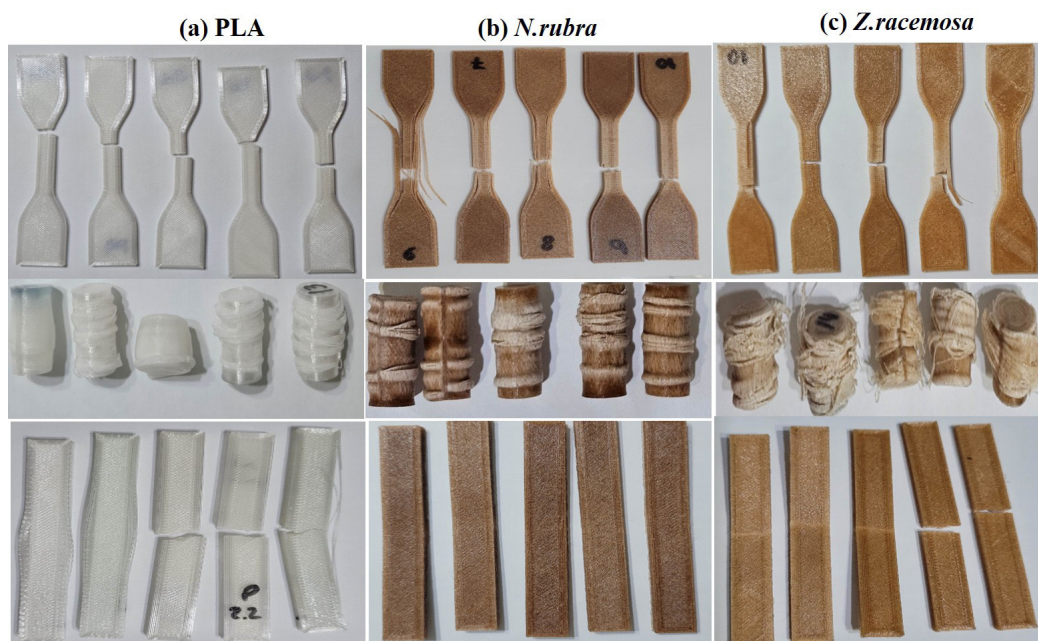


Figure 4. Physical state of the samples after mechanical testing for each formulation (a), (b), (c). From top to bottom: tensile, compression, and flexural results.

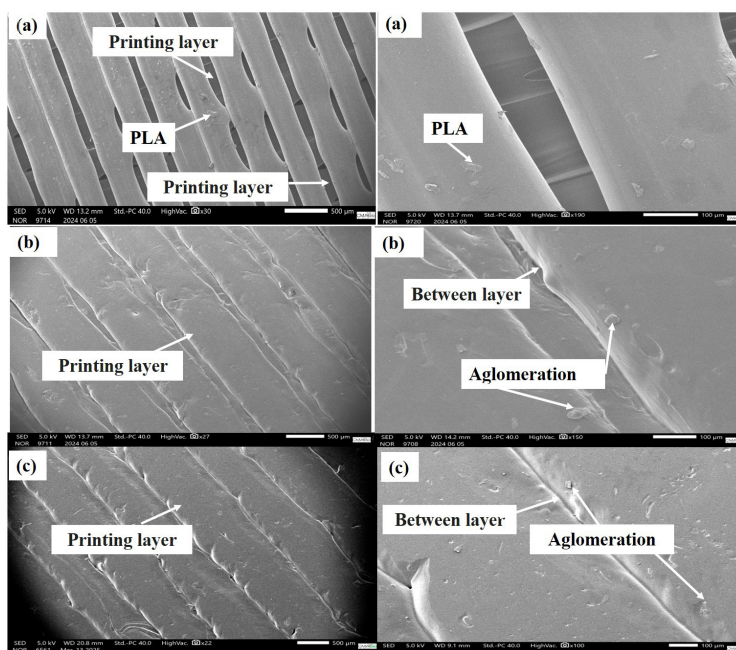


Figure 5. Microscopy of printed parts: (a) PLA; (b) *N.rubra*; (c) *Z.racemosa*.

proportion were satisfactory. Variations in fiber diameter, workability, and residual lignin content can interfere with layer continuity in 3D printing, as heated wood fibers cause thermal changes in the process^[18].

3.5 Thermogravimetric analysis (TGA and DTG)

In the first stage of PLA degradation, the water contained in the material was removed, while in second stage the degradation of the molecular chain occurred. After, total degradation occurred, resulting in carbonization process in ashes^[10]. The thermal degradation of PLA had an initial temperature (Ti) of 295°C and mass loss (Tdeg) of 364°C, with a maximum peak of derived thermogravimetry (DTG) of 348°C, intermediate in relation to the other formulations, and presented a less loss of residue after carbonization of 95% in relation to the composites, with a final temperature (Tf) of 420°C (Figure 6a).

For wood, thermal degradation typically involves distinct stages: the evaporation of water and volatile compounds between 100°C and 200°C, followed by the complete degradation of hemicellulose in the range of 200°C to 300°C^[24,25]. Cellulose degradation generally commences between 300°C and 400°C^[24], while lignin degradation occurs over a broader range of 300°C to 500°C^[26].

With the addition of wood, *N. rubra* showed an initial decomposition of 278°C and mass loss at 331°C, with a final residual mass 45% higher at 446°C compared to PLA and *Z. racemosa* (Figure 6a). DTG curve shows that the maximum decomposition rate peaked at around 311°C (Figure 6b). Comparing with related works, Tao et al.^[10] reported that sawdust from the species *Populus* spp., with a low to medium wood density between 0.36 and 0.56 g/cm³ in combination with PLA, showed a lower temperature and

higher residual mass compared to pure PLA. The commercial PLA filament with cedar fibers *Cedrela* spp. had mass loss above 240°C, while the wood of this species has an average density between 0.43 g/cm³ and 0.52 g/cm³^[19]. The low thermal stability and high residual mass of these species were similar to *N. rubra*. There was an increase in the thermal stability of the composite and lower residual loss of *Z. racemosa* when compared to *N. rubra*. In turn, *Z. racemosa* initially degraded at 281°C and had a second stage at 396°C (Figure 6a) and a maximum peak (DTG) of 377°C, with a final mass after carbonization of 10% at a temperature of 450°C (Figure 6b). Because of its high density, it is possible that a higher temperature was required to decompose the material until combustion. In general, both species can be used in 3D printers using FDM method, with recommended temperature for PLA filament, which is 200°C to 210°C.

3.6 Fourier Transform Infrared Spectroscopy (FTIR)

The vibrational spectra of the printed PLA, composites, and biomass (sawdust powder) are presented in Figure 6c and Figure 6d. Overall, chemical interactions between the polymer and the sawdust are suggested by the observed spectra. The molecular vibrations associated with pure PLA were more intense, while the peaks corresponding to the *N. rubra* composite were less intense compared to *Z. racemosa*. The biomass peaks for both species exhibited similar characteristics, with minor variations between them.

A prominent biomass band at 3332 cm⁻¹ indicates OH stretching, typically related to hydroxyl groups in cellulose^[27,28]. This particular region is notably absent or significantly diminished in the composites of both *Z. racemosa* and *N. rubra*, suggesting interaction or masking by the PLA matrix. The peaks at 2996 cm⁻¹ and 2918 cm⁻¹ in the samples,

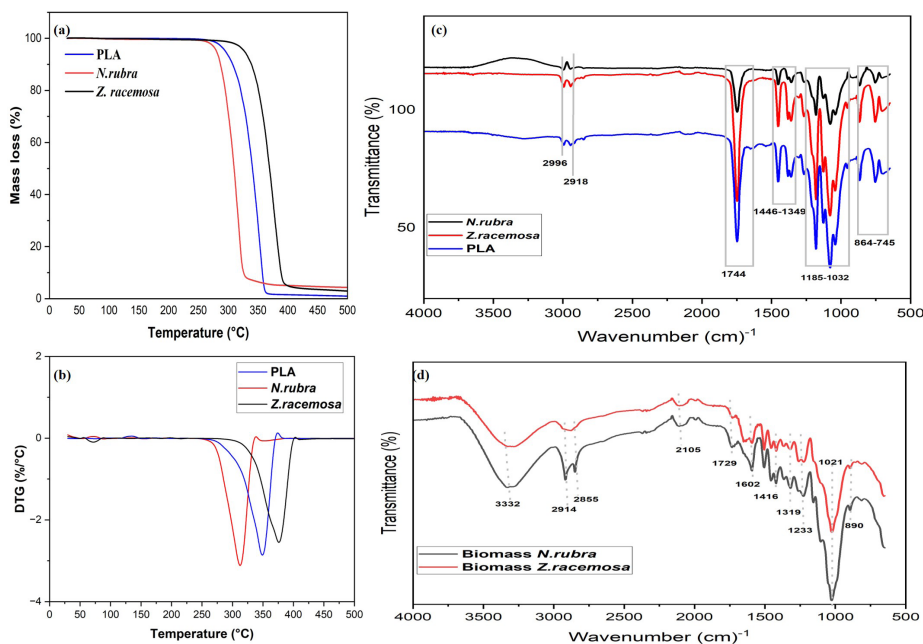


Figure 6. Sample characterization. (a) TGA; (b) DTG; (c) FTIR of PLA, *N. rubra*, *Z. racemosa*. (d) FTIR of sawdust powder from wood (biomass) of *N. rubra* and *Z. racemosa*.

and 2914 cm^{-1} and 2855 cm^{-1} in the biomass, represent the CH stretching of methyl and methylene groups, which are characteristic of the cellulose, lignin, and hemicellulose content in lignocellulosic materials^[22,28,29]. These bands were observed with less intensity in the *Z. racemosa* composite (Zr/OCB).

In the sawdust powder, the peak around 1729 cm^{-1} is associated with the carbonyl C=O group in hemicellulose^[27] appearing more prominent in *N. rubra* biomass. For the printed samples, the intense band at 1744 cm^{-1} corresponds to the carbonyl C=O stretching of the lactide group in PLA^[22]. The band at 1602 cm^{-1} in the sawdust spectra corresponds to water absorption^[30]. In biomass, the band at 1416 cm^{-1} are related to lignin and xylan due to CH_3 bending vibrations^[31]. In the printed samples, the bands between 1446 cm^{-1} and 1349 cm^{-1} correspond to bending vibrations CH_3 ^[22].

In biomass, the band at 1319 cm^{-1} is attributed to deformations in the C—H bonds found in cellulose and hemicellulose^[27]. The band at 1233 cm^{-1} is associated with the C—O present in cellulose, hemicellulose, or lignin^[27,29]. A prominent peak observed at 1021 cm^{-1} is attributed to the C—O, C—C or C—OH, characteristic of cellulose and hemicellulose^[32]. These bands mentioned previously are more accentuated in the *N. rubra* composite, suggesting a higher holocellulose content in this species compared to *Z. racemosa*. Based on these results, it is hypothesized that the greater workability observed for *Z. racemosa* during extrusion is likely due to its specific fiber characteristics and closed pores, in addition to residual lignin content after degradation, rather than being significantly affected by its holocellulose content. This is because wood fibers generally require high temperatures for degradation^[33]. In the printed samples, the region from 1185 cm^{-1} to 1032 cm^{-1} encompasses spectra typically classified as C—O—C stretch^[22].

The band 890 cm^{-1} is associated with the glycosidic vibration characteristic of the cellulose structure^[31]. Lastly, the band at 864 cm^{-1} is equivalent to the vibration C—COO and 745 cm^{-1} is associated with skeletal vibrations of methylene groups^[22].

4. Conclusions

This study demonstrated the feasibility of producing 3D printing filaments from PLA combined with Amazonian wood waste (from *N. rubra* and *Z. racemosa*) and Brazil nut oil (BNO) as a natural binder. Despite the low proportion of wood (4% wt), this research provided an alternative for utilizing Amazonian wood waste, both its natural and diverse colors, adding value to discarded materials and promoting sustainable, biodegradable, and non-toxic 3D bioproducts. Furthermore, it integrates the principles of the circular economy, differentiating itself in the market. Mechanically, while the tensile strength (TS) and compressive strength (CS) of the composites decreased compared to pure PLA, the flexural properties, especially the Modulus of Elasticity (MOE), showed an increase of 153% and 155% for *N. rubra* and *Z. racemosa*, respectively. These enhancements suggest that wood fibers, even at low concentrations, can positively influence the elastic performance of printed parts. *Z. racemosa* provided greater thermal stability to the composite due to its chemical composition. FTIR analysis showed no formation of new chemical bonds, but suggested good compatibility between PLA and the sawdust, corroborated by SEM images. The combination of Amazonian wood waste and PLA presents a promising sustainable alternative for the development of biocomposite filaments for 3D printing.

5. Author's Contribution

- **Conceptualization** – Jackeline Lira Bremgartner.
- **Data curation** – Jackeline Lira Bremgartner.
- **Formal analysis** – Jackeline Lira Bremgartner.
- **Funding acquisition** – Jackeline Lira Bremgartner; Lizandro Manzato; Joaquim dos Santos.
- **Investigation** – Jackeline Lira Bremgartner.
- **Methodology** – Jackeline Lira Bremgartner; Vitor Bremgartner; Claudete Catanhede do Nascimento; Lizandro Manzato; Joaquim dos Santos.
- **Project administration** – Jackeline Lira Bremgartner; Joaquim dos Santos; Lizandro Manzato.
- **Resources** – Jackeline Lira Bremgartner; Lizandro Manzato.
- **Software** – Jackeline Lira Bremgartner; Vitor Bremgartner; Lizandro Manzato.
- **Supervision** – Jackeline Lira Bremgartner; Joaquim dos Santos; Lizandro Manzato.
- **Validation** – Jackeline Lira Bremgartner; Vitor Bremgartner.
- **Visualization** – Jackeline Lira Bremgartner.
- **Writing – original draft** – Jackeline Lira Bremgartner; Vitor Bremgartner.
- **Writing – review & editing** – Jackeline Lira Bremgartner; Joaquim dos Santos; Lizandro Manzato; Vitor Bremgartner; Claudete Catanhede do Nascimento.

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