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# Preparation and Characterization of Ecuadorian Bamboo Fiber-Low-Density Polyethylene (LDPE) Biocomposites

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**Abstract**: Synthetic plastics have several concerns for the environment, such as their impact on climate change, their long degradation time, or their degradation to microplastics that threaten animal life in the sea. The application of natural fibers as reinforcement in synthetic polymeric matrixes has several advantages in properties such as low density, lower cost of production, biodegradability, and a reduction of the environmental impact in the polymer industry. In this study, the Ecuadorian Guadua Angustifolia Kunth fiber was extracted and treated physically and chemically for its use as reinforcement in composite preparation. Maleic anhydride was used as a coupling agent to improve the interaction between the natural fiber and the low-density polyethylene (LDPE) polymeric matrix. The composite production was done using different bamboo particle loading (1-5% w/w) at a constant particle size (150 μm). Chemical, physical, and mechanical properties were evaluated to characterize the fiber and biocomposites. The chemical treatment of the fiber with 2% of NaOH showed a reduction of the lignin content confirmed by Fourier-Transform infrared spectroscopy. A total of ~39% mass loss related to the lignin, waxes, and other organic content was reached. In addition, a reduction in the density from approximately 0.87 to 0.66 was shown when increasing the content of bamboo in the composite. In the same way, the crystallinity was reduced by 3%. The composite with 1% bamboo presents a tensile strength of 10,66 MPa. The use of bamboo fiber in the biocomposites reduces the global warming potential concerning the increasing amount of fiber.

Keywords: Natural fibers, Guadúa Angustifolia Kunth, Composite, Plastic films, Thermal and mechanical properties.

## 1. Introduction

One of the most used plastics around the globe is low-density polyethylene (LDPE). This thermoplastic is used for water bottles, food packing, non-food packaging, and other applications[1)]. Plastics have replaced many materials in recent years, and their importance in the everyday life, as well as industry, has grown significantly. However, everyday LDPE ends up in landfills (about 60% of the total waste) where hundreds of years are needed for the plastic to decompose[2)]. Other alternatives that have a less environmental impact have been investigated. One might be using microbial agents to degrade the thermoplastic[2)]. Another might be the use of biodegradable plastics or biodegradable materials that fill the polymer as a composite. For instance, polymer biocomposites that use cellulosic materials are an alternative under research because important properties have been established[3)].

Natural fibers are rich in cellulose which is the most abundant polymer found in nature. These fibers have interesting properties such as biodegradability, less environmental impact, and flexibility, among others[4)]. Natural fibers are being used to reinforce thermoplastics, cementitious materials, and other materials needed in today's society[5,6)]. Fibers such as sisal, jute, cotton, bamboo, or bagasse have been used as reinforcement in materials with interesting results on the mechanical properties of the matrixes[1,3,5,7–9)]. Among this group, one with growing interest is the fiber from bamboo or Guadua Angustifolia Kunth[1,7,10–14)]. The addition of the bamboo

filler in LDPE resulted in an increase in properties like Young's modulus, water absorption, and flexural strength[15,16].

Biocomposites that are prepared using natural fibers and resin have shown that they can be used in structural and non-structural impact applications because of their enhanced thermal stability or loss moduli properties. For this purpose, Jawaid *et al.* [17] prepared several composites incorporating oil palm and pineapple fibers into the biophenolic resin reporting better mechanical properties for hybrid composites which contain both fibers. Similarly, Awad *et al.* [18] evaluated the impact of NaOH-treated and untreated palm and pineapple fiber-reinforced biophenolic composites' mechanical properties. The authors declared that the treated fibers reinforced biocomposites presented better tensile strength and modulus suggesting that the alkali treatment increased the interaction between fiber and the polymeric matrix. On the other hand, Sarmin *et al.* [13] provided added value to different parts of the olive tree to be used as reinforcement material for epoxy-based composite preparations. The authors reported an enhancement in the mechanical properties of the composites. There are some other studies that demonstrate the importance of using several natural fibers as reinforcement for composite preparations. Jawaid *et al.* [19] evaluated the thermo-mechanical properties of date palm/bamboo fiber-epoxy hybrid composites indicating superior thermal stability and expansion compared to the composites that contain only one fiber. Likewise, Yorseng *et al.* [12] also reported better mechanical properties for bamboo, basalt, and carbon-reinforced hybrid composites. The authors additionally compared synthetic and bio-based epoxy hybrid composites indicating preferable results in favor of bioepoxy-based ones and recommending the replacement of synthetic resin with bio-based ones. Salim et al. [14] studied water absorption of bamboo and flax fibers filled epoxy hybrid composites at room temperature and 85 °C and its impact on mechanical and swelling properties. The authors reported that the composites containing treated fibers with 9% of NaOH showed better swelling properties.

The market and societal needs have ignited an exponential growth in the demand for polymers. This results in environmental impacts that have significant burdens on the ecosystems that should be considered. In this sense, the United Nations have established goals to achieve sustainable development of societies[20]. The composite using bamboo and LDPE results in a material that has better environmental performance than its full synthetic polymer. The environmental impact of polymers and other materials can be assessed through a life cycle (LCA) perspective. The LCA for different polymers (bio and synthetic) has been performed with a cradle-to-gate or cradle-to-grave approach[21]. Using the life cycle assessment, a sustainable material can be developed for different applications.

This is one of the first studies that consider the use of cellulose enriched-bamboo fiber in the preparation of polyethylene-based biocomposites. We add value to a plant that is normally used as supporting material in the construction industry in Ecuador. The present study aims to prepare a polymeric biocomposite that utilizes bamboo (Guadua Angustifolia) as a filler and low-density polyethylene (LDPE). Bamboo fibers were treated to obtain cellulose-enriched bamboo fibers to be used as reinforcement materials in the LDPE matrix. Treated bamboo fibers and corresponding bamboo fiber-LDPE biocomposite's physicochemical properties have been characterized using FTIR, SEM, optical microscopy, and mechanical testing techniques.

## 2. Materials and Methods

Pure LDPE from PEMEX as a pellet was used as the polymeric matrix (PX 20020 P, Petrochemical Company PEMEX). Maleic Anhydride reagent grade was utilized as a coupling agent. The natural fibers were obtained from Guadua Angustifolia Kunth bamboo specie, originally from southern Manabí state, Ecuador.

### 2.1. Treatment of the Natural Fiber

#### 2.2.1. Mechanical and Thermal Treatment

A size reduction of long bamboo culms was performed to obtain (2x2x10 $cm^3$) strips. The culms were chopped into smaller pieces using a roll crusher. Air-dried strips were reduced in size using a hammer mill. The homogeneous small particles were separated using a 150 µm sieve from a sieve shaker Tyler Model RX-818, Taylor Scientific. The sieved fibers underwent a hydrothermal process at 100°C for 30 minutes and then dried in an artisan tray drier at 45°C for 6 hours.

#### 2.2.2. Chemical Treatment

Chemical fiber modification was applied to increase the interfacial adhesion between the natural and synthetic polymers. Different methods can be applied to remove lignin or hemicellulose from the bamboo fibers[22]. For this study, the fibers were soaked in a NaOH solution (2 wt.%) at a ratio of 1:12 (NaOH solution/water) for 18h. Then, the treated fibers were neutralized and dried again in the tray drier at 45°C for 6 more hours.

### 2.2. Bamboo fiber-LDPE biocomposite preparation

Several samples of biocomposites were prepared. In total 5 different samples were produced varying the fiber content. All biocomposites (BFPE) have 1% of maleic anhydride coupling agent (MA), Guadua Angustifolia fiber (GAF) load varies from 1 to 5%, and a remainder percentage correspondent to LDPE. Table 1 shows the composition of each mixture.

Table 1. Mix design of bamboo fiber-LDPE biocomposites

| Sample | LDPE (%) | GAF (%) | Maleic anhydride (%) |
|---|---|---|---|
| BFPE1 | 98 | 1 | 1 |
| BFPE2 | 97 | 2 | 1 |
| BFPE3 | 96 | 3 | 1 |
| BFPE4 | 95 | 4 | 1 |
| BFPE5 | 94 | 5 | 1 |

The LDPE pellets, the fiber, and the coupling agent were dry-blended in the first phase of the simple screw extruder. The extrusion process followed the recommended conditions for processing LPDE on the technical sheet. The biocomposites were obtained in pellet form. The following step was the processing of the plastic films using a blowing film extruder that resulted in 200 µm thick plastic sheets.

### 2.3. Performance Properties measurement

#### 2.3.1. Characterization of Guadua Angustifolia Kunth/Ecuadorian Bamboo

Pure/untreated Guadua Angustifolia Kunth bamboo and thermally treated bamboo fiber were chemically characterized according to the standards given in table 2.

Table 2. Standards for GAF fiber chemical characterization

| Standard | Parameter |
|---|---|
| T412 om-11 [23] | Moisture Content |
| ASTM D1103 [24] | Cellulose |
| T222 om-02 [25] | Lignin |
| T204 cm-97 [26] | Oils, Fats & Resins (OF&R) |

#### 2.3.2. Infrared Spectroscopy (FTIR)

Samples were analyzed under an inert atmosphere using the Thermo Scientific model Nicolet iS10 infrared spectrophotometer. KBr discs of the samples were prepared using 25 wt.% of fiber mixed with dry KBr. Additionally, plastic films (5x5 $cm^2$) of the GAF-LDPE were analyzed. The spectra of the samples were analyzed with the OMNIC software.

#### 2.3.3. Morphological Characterization

The morphology of the LDPE matrix with the bamboo fibers as a composite was observed using scanning electron microscopy (SEM, FEI Inspect S50 model, FEI Co., Hillsboro, TX, USA). An acceleration voltage of 15 kV was applied with a gold-palladium (Au-Pd) coating.

Superficial and particle dispersion analyses of the composite and pure LDPE samples were done using an INDUS optical and industrial microscope.

#### 2.3.4. Thermal properties

GAF fiber, GAF biocomposites, and pure LDPE were analyzed on a TA Instruments Q-600, STD simultaneous thermal analyzer. Thermal properties were determined by applying thermogravimetry (TGA) and differential scanning calorimetry (DSC) techniques. TGA-DSC analyses were carried out in a temperature range between 43 – 1000 °C with a heating ramp of 10°C/minute and under a constant nitrogen flow of 50 mL/min.

#### 2.3.5. Mechanical Properties

The tensile properties of the GAF and pure LDPE composite sheets were determined by a universal testing machine SHIMADZU AG-IS 10 kN according to the ASTM D-882 standard, where evaluation in specimens was parallel and perpendicular to the flow.

#### 2.3.6. Density measurements

The density of pure LDPE and corresponding BFPE biocomposites has been carried out according to method A described in ASTM D729[27] norm which requires an analytical balance with a precision of 0.1 mg and distilled water. The density measurement of each sample was triplicated.

The density of the samples was measured on a Mettler Toledo XP205 analytical balance and distilled water was used as the reference liquid as indicated in the norm[27].

#### 2.3.7. GAF fiber weight loss along the treatment

GAF fibers were treated in three steps. The first step was washing the fibers with water. The next step is a thermal-hydrothermal treatment which is putting the fiber in boiling water for 30 minutes with continuous agitation. The last step is the chemical treatment of fibers with a 2% NaOH solution. The weights of the fibers have been recorded at each step to calculate the changes. For this purpose, each sample first has been dried at 105°C for 3 hours using a MEMMERT oven and then the weights. The quantity of the samples at each step was measured using a Mettler Toledo XP2004S analytical digital balance.

## 3. Results and discussion

### 3.1 Characterization of Guadua Angustifolia Kunth

The chemical composition of the GAF fiber is shown in Table 3. The cellulose content of the pure GAF fiber is near the range of 40-48% of total mass according to Scurlock et al. 22). But after the treatment cellulose content increases to 67,11%, which is consistent with the study reported by Khalil et al. [10]. It is known in the literature that the lignin content in pure fiber is in the range of 25-30%[28]. The variations in composition depend on different factors such as age and origin[29]. Generally, cellulose content tends to decrease as the bamboo becomes older. The OF&R content is important because they provide color, odor, and degradation resistance.

Table 3. Guadua Angustifolia Kunth Ecuadorian bamboo chemical composition

| **Parameter** | **Content (%)** **Pure/untreated fiber** |
|---|---|
| Moisture | 1,80 |
| Dry Basis Content | |
| Cellulose | 33,51 |

The chemical treatment of the GAF fiber is a very efficient method for fiber preparation as seen in Table 3. The hemicellulose content diminished greatly. Removing the hemicellulose layer from the fiber allows for cellulose hydroxyl groups to interact with the water molecules from the environment. This resulted in a higher content of moisture in the treated bamboo fiber.

The treatments (washing, thermic and chemical) partially extracted the lignin and most of the hemicellulose. The dissolution of the crosslinking hemicellulose layer does not appear in figure 4 anymore. Lignin, otherwise, is mostly removed after the chemical treatment.

Table 4 shows the total weight loss of the treated fibers. Weight loss should be considered in the fiber-LDPE composite because about 39% of the total mass is removed in the treatment steps.

Table 4. GAF fiber weight loss concerning each treatment.

| **Treatment** | **Description** | **Mass loss (%)** |
|---|---|---|
| Physical Treatment | Washing with distilled water | 6.91 |
| | Hydrothermal treatment | 2.36 |
| Chemical Treatment | Treatment with 2% NaOH solution | 29.93 |
| Total mass loss | -- | 39.20 |

Figure 1 shows the FTIR for the treated and untreated bamboo fibers. It is observed that in all spectra there are characteristic peaks that correspond to the hydroxyl group interactions ( 3360 $cm^{-1}$), carbon-hydrogen bond (2910 $cm^{-1}$), carbon-carbon double bond stretching from the aromatic skeleton (1600 $cm^{-1}$), methyl group stretching (1424 $cm^{-1}$), carbon-oxygen bond (1207 $cm^{-1}$) [30,31]. Around 1731 $cm^{-1}$, the corresponding peak from lignin´s unconjugated C=O stretching bond[32] is not present in the chemically treated GAF fiber's spectrum. On the other hand, this same peak appears in the other two spectra. These changes confirm the effectiveness of each process, especially chemical treatment for the removal of hemicellulose, lignin, and other water-soluble compounds. This process increases the quantity of cellulose in the final fiber obtained.

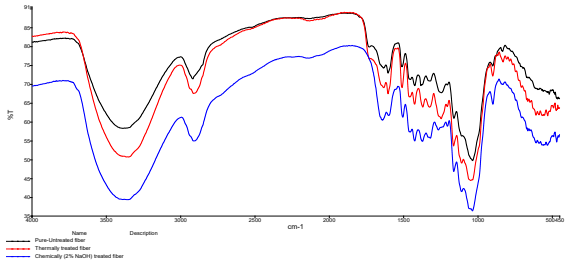

**Fig. 1:** FTIR spectra of pure (untreated), washed, and chemically treated GAF fibers.

The results of thermogravimetry and differential scanning calorimetry of the fibers can be observed in Table 5. The thermogram of Figure 2 shows the clear difference in the thermal behavior of the fibers at different stages of their treatment. The treated fiber presented high moisture content; therefore, it is recommendable to maintain controlled environmental conditions as a critical factor in composite preparation. At the end of the hydro-thermal treatment, a considerable percentage of inorganic components were removed. This is because the residual content of the hydrothermally treated fiber is less than the pure GAF fibers. But in the case of the chemically treated fiber, this content increases again. It is reported[33] that sodium-cellulose can be formed at higher concentrations of NaOH solution. Besides that, chemical treatment with NaOH in order to improve the cellulose content may have led to the formation of Na-cellulose derivatives, as reported in the literature[34]. As the concentration of NaOH solution is not high, the residue of chemically treated fiber

is slightly higher than the untreated sample which might be due to the very low amount of Na-cellulose formed.

Table 5. Thermogravimetric and differential scanning calorimetric analyses of GAF fiber at various treatment stages

| Sample | Moisture Content (%) | Residual Content (%) | 1st weight loss | |
|---|---|---|---|---|
| | | | Range 1 [°C] | $T_{max}$ [°C] |
| Pure/ | 7,284 | 27,596 | 39,03-142,64 | 73,57 |
| Hydrothermally treated fiber | 11,85 | 14,72 | 39,03-140,72 | 73,57 |
| Chemically treated fiber | 9,612 | 22,97 | 42,24-158,25 | 75,14 |

| Sample | 2nd weight loss | | $\Delta H_{Water\ evaporation}$ |
|---|---|---|---|
| | Range 2 [°C] | $T_{máx}$ [°C] | [J/g] |
| Pure/ | 167,59-679,88 | 316,28 | 217,2 |
| Hydrothermally treated fiber | 208,84-664,53 | 350,82 | 309,6 |
| Chemically treated fiber | 182,46-573,84 | 311,58 | 195,1 |

The first weight loss is the result of water and organic volatile components[35]. During the second weight loss, the pure fiber's behavior was different from its biocomposites. The maximum temperature corresponds to the thermal degradation temperature of the fiber. The final treated fiber presents a similar maximum temperature to the pure fiber. This suggests that thermal degradation characteristics are maintained after chemical treatment.

As it is observed in table 3, the chemically treated fiber (2% NaOH) has the greatest moisture content. Table 5 confirms this with 7,9 % moisture content. Also, it presents residual content of 23% w/w humidity (43°C – 1000°C). Despite the greater thermal stability considering onset temperature, the hydrothermally treated fiber, contains the highest water content. The increase in onset temperature has also been reported by Chen et al. [36] describing the increase concerning the chemical treatment with NaOH treatment. We observed the same tendency in the current study.

According to the behavior of the chemically treated fiber, and to enhance the adhesion in the LDPE polymeric matrix, it was necessary to keep the fiber dry and under controlled conditions.

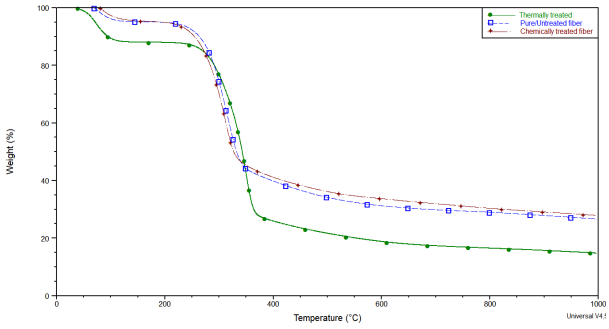


**Fig. 2:** TGA analysis of pure/untreated, thermally and chemically treated fibers.

Figure 3 (a, b, c) shows the SEM images obtained for the fiber both pure and treated (thermally and chemically). It shows the morphology or surface of the biopolymers. All its constituents are intact and even the porous network surrounding the cellulose is seen. This network is made up of hemicellulose[37]. Figure 3 b) shows the state of the fiber after the thermal hydro treatment. The porous network of hemicellulose has been removed. Longitudinal fibers are observed together on a binder substance, known as lignin. This arrangement of the fibers can be considered crystalline[38]. Figure 3 c) shows the evident superficial modification and the smoothness and cleanliness of the fibers. This is due to the chemical treatment that eliminates lignin.

### 3.2 GAF-LDPE composite characterization

The density of the composite was determined to establish the effect of bamboo fiber content on this property. Guadua Angustifolia Bamboo (BF) has a very low density. Therefore, as shown in Figure 4 the density of the composite decreased as the content of fiber increased. The composite BFPE4 shows a slightly higher density that might be related to the part of the polymer film studied. Distribution of the biopolymer can be heterogenous and cause this effect on the studied data. As said, it might be due to a poor distribution of the fiber in the LDPE matrix. Figure 7 shows agglomerations and mal-dispersion of the fibers inside the matrix. Different parts of the biocomposites may show different densities as there is not a homogenous dispersion of the fibers. However, the tendency clearly shows a decrease in the density of the BFPE biocomposites.

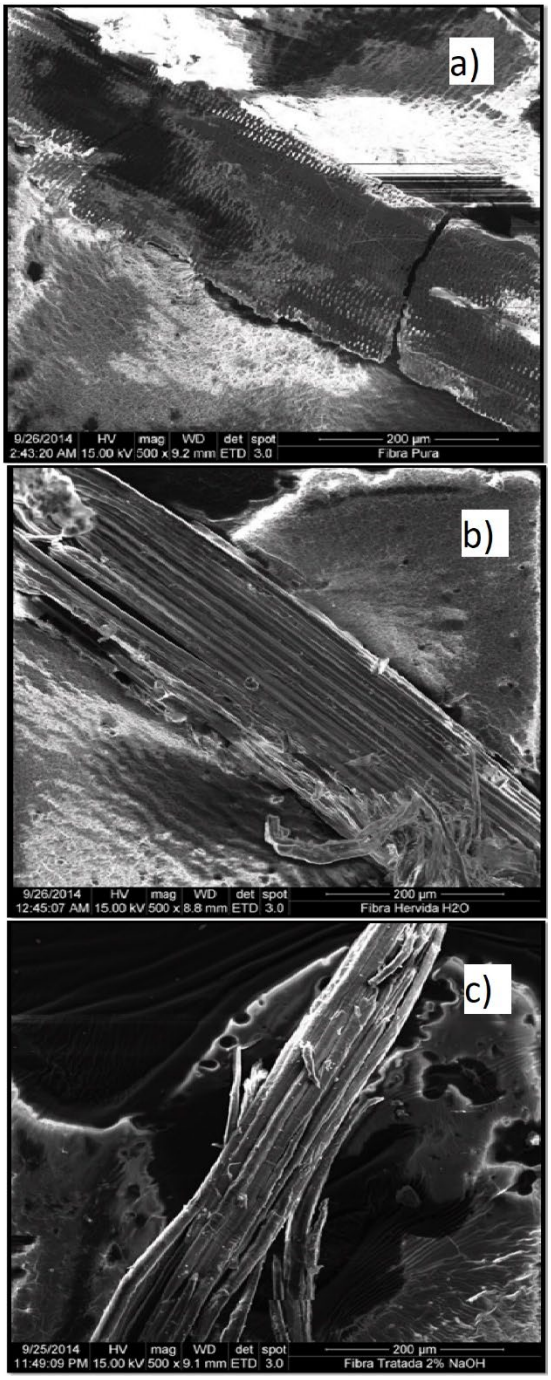


**Fig. 3:** Microstructures of a) pure/untreated, b) hydrothermally treated, and c) chemically treated GAF fibers.

This behavior can be associated with various factors. The sample of biocomposites analyzed was in pellet form. Despite the controlled conditions during the preparation process of the biocomposites, homogeneity in the distribution and dispersion of the fibers throughout the polymeric matrix, air bubbles, vapor, and other volatile substances affected the resultant density.

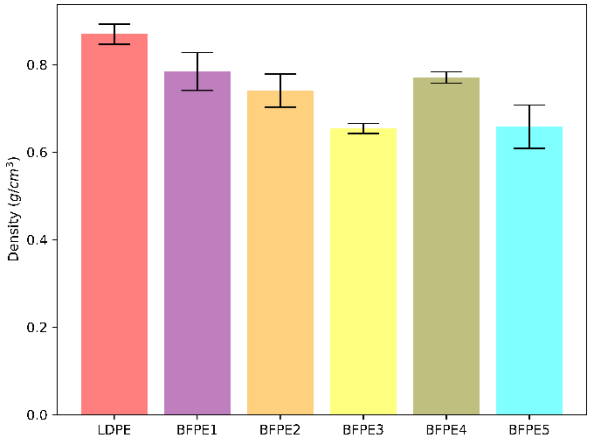


**Fig. 4:** The densities of pure LDPE and its corresponding biocomposites.

The LDPE and its corresponding biocomposites were analyzed by FTIR spectroscopy. The polymeric chain of the LDPE is made up of long and branched chains of carbon-hydrogen atoms. The typical vibrations shown in FTIR spectra are associated with carbon-carbon and carbon-hydrogen bonds.

Figure 5 shows the FTIR spectra of LDPE and the biocomposites. The high-intensity peaks of 2915 $cm^{-1}$ and 2847 $cm^{-1}$ approximately are due to the stretching of C-H bonds present in the structure of LDPE 33). Near 1507 $cm^{-1}$, it was determined that there was a stretching interaction of the double C=C bond, due to the aromatic skeleton of lignin. In the 1472 $cm^{-1}$ wavelength, there is a scissor vibration due to the C-H bond from the alkane group $-CH_3$. Near 1463 $cm^{-1}$, it is also associated with the C-H stretching peaks due to the $-CH_2-$ groups. The vibration from the C-O bond that was detected around 1118 $cm^{-1}$ was associated with cellulose, hemicellulose, and lignin. The other peaks overserved at 1377 $cm^{-1}$ and 719 $cm^{-1}$ are due to the vibrations of groups $CH_3$ and $CH_2$, respectively [7,15,39].

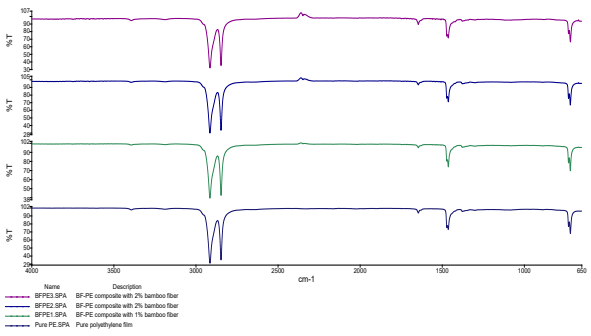


**Fig. 5:** FTIR spectra pure LDPE and its corresponding biocomposites.

Because of the low content of fiber in the LDPE matrix, the trend of the DTG curves of the biocomposites is very similar to the one of the synthetic fibers (LDPE), in contrast with the curve related to the GAF. Even though, a small peak is detected near the primary peak of the DTG

curve of BFPE3. This peak is associated with the GAF content present in the matrix (see figure 6).

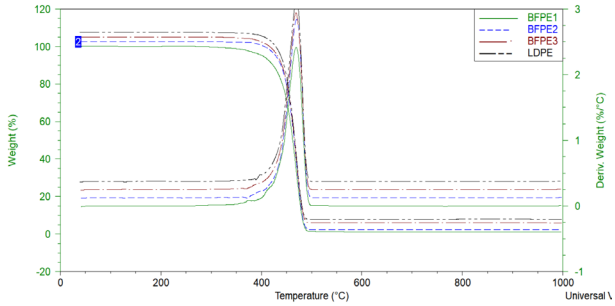


**Fig. 6:** TGA-DTA analysis of pure LDPE and its corresponding biocomposites.

The synthetic matrices, due to the oil derivative nature of their origin, present a high resistance to biodegradation processes. At inert conditions, the degradation temperature of thermoplastics is higher in comparison to the corresponding in a corrosive environment[2]. The addition of GA (bamboo) fibers in the synthetic matrix of LDPE affects the degradation temperature of the bio-biocomposites as expected. The higher the fiber content, the lower the degradation temperature. The melting temperatures (Tm) obtained do not portray significant differences. These temperatures are near 130 °C (see table 6). The melting temperature of LDPE determined by the study of Wong and Lam[40] was 112,4 °C. The LDPE used in this study could have less amount of ramifications in its polymeric chain, having greater thermal stability[40].

Table 6. DSC results of LDPE and GAF-LDPE biocomposites.

| Sample | $T_m$ (°C) | $\Delta H_m$ (J/g)* | $T_{id}$ (°C)** | $T_d$ (°C)*** | $\Delta H_d$ (J/g) |
|---|---|---|---|---|---|
| **LDPE** | 132,99 | 55,88 | 445.45 | 474,63 | 199,5 |
| **BFPE1** | 130,51 | 42,71 | 445,52 | 474,63 | 187,2 |
| **BFPE2** | 131,73 | 41,21 | 442,47 | 474,18 | 222,2 |
| **BFPE3** | 130,76 | 39,42 | 436,3 | 472,39 | 318,7 |

*Melting enthalpy, **: initial degradation temperature, ***: degradation temperature

The biocomposites show a reduction in the melting enthalpy as the LDPE is replaced by a percentage of bamboo. In fact, a reduction of ~42% in the energy needed to melt the material was observed between the pure LDPE and the composite with 3% bamboo fiber. The biocomposites show similar thermal stability compared to the pure LDPE. This also occurs in the degradation temperature (second process), to the initial temperature (Tid), and the maximum degradation temperature (Td). On the other hand, it is shown that the values corresponding to the melting heat (ΔHm), are significantly variable among them, having BFPE1 as the most stable. The second process is more critical. The amount of energy required (ΔHd) for the degradation of the sample varies very much. The BFPE3 has the highest value of 318,7 J/g of all the composite samples, even higher than the LDPE value of 199,5 J/g. The max degradation temperature was not affected by the addition of the fiber, and only a slight change was seen in the onset degradation temperature. The Td or peak of degradation is in the range of 472-474°C. This differs from the findings of Yorseng *et al.* [12] using bamboo as a filler, they reported a reduction of about 20-30°C in the degradation temperature. However, the main difference relies on the organic content found in the bioepoxy composite in which more than half of the weight is plant origin. Literature shows similar behavior to the thermogravimetric curve, the degradation of biocomposites is completed after 400 °C, and a mass loss is observed around 100°C due to the evaporated water[41].

The crystallinity of the composite has been calculated using the following formula[42]:

$$Xc = \frac{\Delta Hm}{\Delta Hm^{T} * (1-w)} * 100\% \qquad (1)$$

Table 7 shows the results of crystallinity for the biocomposites using the enthalpy of fusion or heat of fusion. The tendency shows a reduction of the crystallinity when the bamboo fiber content increases. The theoretical heat of fusion was obtained from the literature[43]. Literature shows a value of crystallinity for the LDPE used in this study of approximately 27%[44]. Therefore, the result obtained is within the degree of uncertainty, processability, and other factors that may affect the crystallinity of the polymer.

Table 7. DSC-based crystallinity results of LDPE and GAF-LDPE biocomposites.

| Sample | $\Delta H_m$ (J/g) | LDPE (%) | $\Delta H_m$ (J/g) | Crystallinity (%) |
|---|---|---|---|---|
| **LDPE** | 55,88 | 100 | 280 | 19,86% |
| **BFPE1** | 42,71 | 98 | | 15,65% |
| **BFPE2** | 41,21 | 97 | | 15,73% |
| **BFPE3** | 39,42 | 96 | | 14,67% |

The optical industrial microscope showed more information about the morphology of the polymer and its isotropic nature. As well as to observe the GA fiber dispersion in the LDPE matrix of the composite film. Figure 7 shows the surface of the polymer and

biocomposites. Figure 7 a) shows pure LDPE film, characterized by isotropy. Small irregularities seen in the image can be attributed to the processing effects in the extrusion process. Figure 7 b) corresponds to the BFPE1 film. The distribution of the fiber is good, its orientation is random, and the dimensions of the fibers vary in length and width. No presence of bubbles is appreciated, but some agglomerations are also observed. As shown in figure 7 c), the studied composite has a slightly homogeneous fiber dispersion, and it is similar to the (BFPE1) film. Even though, in this composite film, LDPE lumps and lashes appear on the surface. These particles seem to point in the direction of the extrusion flow (Fig 7 c)). As it is shown in Fig. 7 d), greater and more lashes appeared on the surface. These lumps present irregular elliptical forms. Its sizes are variable and sometimes appeared to be overlapped between them. It also seems to be encapsulated air bubbles in the surface of the composite film. This can be due to the deficient mixture during the extrusion process or to insufficient use of coupling agent (MA), which was a constant 1 wt.%.

The results obtained from studying the mechanical properties are presented in table 7, which details the maximum load, maximum effort, and maximum elongation. This corresponds to the probes prepared longitudinally. The average thickness of these films was 201,8 μm. The BFPE1 presented only a ~7% difference between the composite maximum load vs the pure LDPE.

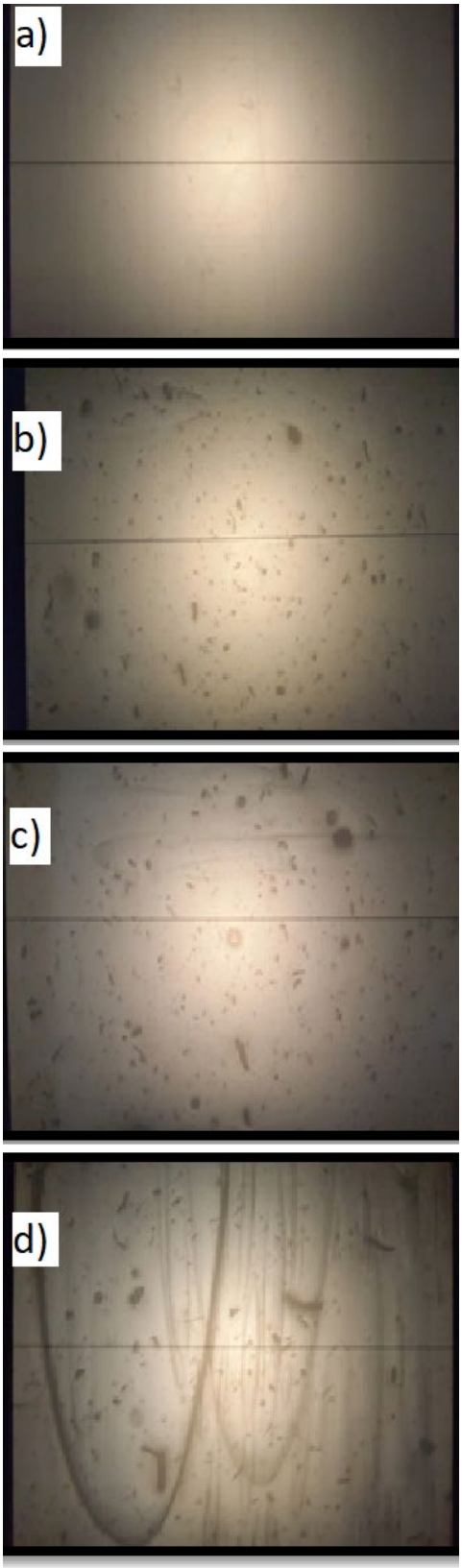


**Fig. 7:** Optical image of a) pure LDPE film, b) BFPE1 film, c) BFPE2 film, and d) BFPE3 film.

In addition, Fig. 8 shows the modulus and force applied to the polymer/biocomposite and elongation resulted from the tensile strength test. The pure LDPE shows more elongation than the composite because of the filler

bamboo fibers that cause the composite to rupture because of the particles added. However, Figure 8 gathers the average curve for five samples per filler content showed that the BFPE1 curve demonstrates good resistance to the force applied when compared to pure LDPE. This result indicates that the first composite is a potential raw material to produce plastics. From all the synthesized biocomposites, the BFPE1 presented the best properties, with good thermal stability and acceptable mechanical properties. Thus, it contains the optimum fiber content.

Table 7. Mechanical Properties of LDPE and composite films.

| CODE | Average Modulus [N] | Standard Deviation (±) |
|---|---|---|
| **LDPE** | 29.21 | 2.45 |
| **BFPE1** | 26.92 | 2.08 |
| **BFPE2** | 20.16 | 2.18 |
| **BFPE3** | 17.72 | 2.23 |
| **CODE** | **Average Compressive Strength [N/mm$^2$]** | **Standard Deviation (±)** |
| **LDPE** | 11.57 | 0.97 |
| **BFPE1** | 10.66 | 0.82 |
| **BFPE2** | 7.98 | 0.86 |
| **BFPE3** | 7.02 | 0.88 |
| **CODE** | **Average Deformation [%]** | **Standard Deviation (±)** |
| **LDPE** | 871.21 | 68.08 |
| **BFPE1** | 29.81 | 5.39 |
| **BFPE2** | 28.00 | 1.66 |
| **BFPE3** | 29.75 | 3.04 |

### 3.3 Life cycle assessment (LCA)

The environmental evaluation under the life cycle was based on the ISO statute 14040[45]. For this study the assessment considers literature published for different uses of bamboo in materials. The use of treated bamboo fibers in the LDPE matrix is yet to be defined through the LCA. The LCA should consider the use of reagents for the treatment of the fiber and its addition to the polyethylene matrix. One study assessed the environmental impact of the use of bamboo in laminated polymer composite[46]. The results showed a reduction of 50% in the climate change indicator, almost 70% for ozone depletion, except for the ecotoxicity category, every indicator showed a positive performance when bamboo is incorporated. Similarly, another study[47] evaluated the use of bamboo for board application and compared it to other materials like concrete, and aluminum-based materials. The bamboo board all performed with positive impacts on the environment by reducing greenhouse gas emissions, while steel, concrete, or polyvinyl chloride (PVC) had negative repercussions. In the current study, it is estimated that around a 13% reduction of global warming potential for the incorporation of bamboo fiber in composite and a possible further reduction when more bamboo is used which requires less quantity of LDPE used. However, the indicator that might raise a higher impact is the water consumption category because water is needed in the agro-industrial phases of growing the bamboo in addition to the water needs of processing the wood to obtain the fiber.

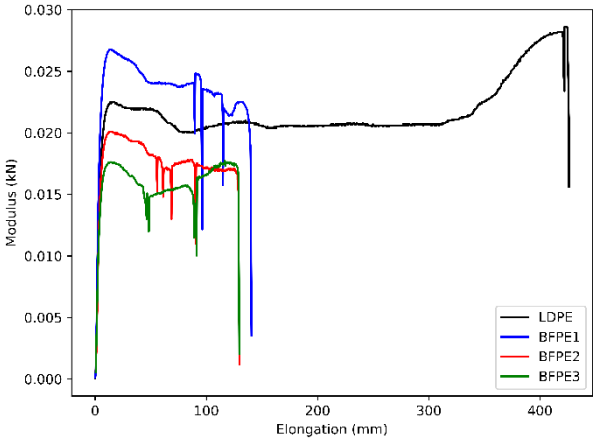


**Fig. 8:** Strength vs elongation curves. for the pure LDPE and its bamboo fiber-reinforced biocomposites.

## 4. Conclusions

Biocomposites of LDPE were prepared by extrusion using Guadúa Angustifolia fibers (150 µm) as reinforcement of the polymeric matrix. Mechanical, physical, and chemical properties were analyzed to assess the material as a replacement for pure synthetic polymer.

Effective chemical and hydrothermal treatments were applied to the fiber to obtain the highest reduction of lignin and hemicellulose from the BF. A reduction in the polarity and thermal stability was observed in the fibers that were used as reinforcement for the polymeric matrix.

Among the BFPE biocomposites prepared, the composite implementing 1% of fiber (BFPE1) presented the best physical and mechanical properties. A reduction of density due to the content of fiber was obtained while maintaining a similar thermal behavior compared to pure LDPE. As expected higher percentages of fiber in the composite lowers the mechanical and physical properties of those biocomposites.

Polarity could be further explored to enhance the compatibility of the polymer and biopolymer fiber. The use of a more concentrated NaOH solution and a coupling agent may provide the solution to the compatibility problem of the materials. In addition, studies assessing the

particle size of the fiber (<150 um) in the polymer could result in better dispersion in the materials.

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