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Biocomposites from Colombian Sugarcane Bagasse with Polypropylene: Mechanical, Thermal and Viscoelastic Properties

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.80753>

Abstract

Biocomposites are materials formed by mixing a polymer matrix and a filler or reinforcement, with the characteristic that at least one should be of biological origin. For this study, biocomposites were obtained from natural fibers of cane bagasse and polypropylene, using bagasse from postindustrial sources, originating from the production of sugarcane from the Valle-Cauca region in Colombia. In addition, cane bagasse fibers were treated chemically, with the purpose of improving the interfacial relationship. Polypropylene homopolymer was used as a polymeric matrix, which was mixed in a twin screw extruder, obtaining different materials as biocomposites. Finally, it was possible to obtain a suitable biocomposite for application in injection molding processes and studying its mechanical, viscoelastic, and thermal behaviors, through DSC, TGA, DMA, and SEM techniques.

Keywords: biocomposites, sugarcane bagasse, mechanical properties, thermal properties, DMA

1. Introduction

Since several decades ago, biocomposites have emerged as an option aimed to solve several issues within the composite materials science. In most of published cases in the literature, the use of natural fibers in combination with polymers is carried out to achieve some degree of reinforcement from the fibers to the polymer. Many studies report the use of natural fibers such as flax, hemp, jute, sisal, coconut fiber, banana, and fique, among many others [1], using

an extensive variety of polymer matrices like polyethylene [2, 3], polypropylene [4], polystyrene [5], polyester resins [6], and natural rubber [7]. Clear effects have been seen in the improvement of mechanical performance. For example, usually Young's modulus and tensile and flexural strength increase when natural fibers are compounded in percentages from 10 to 40%, which make the composites stiffer than its matrix counterpart [8]. Also, improvement in impact strength has been observed [9]. These findings give to the natural fibers a real opportunity to replace to some extent the use of fiberglass, aramid, and other synthetic fibers usually used for polymer reinforcement since, on top of their reinforcement ability, natural fibers are also cheap and have a much lower density than fiberglass, as previously stated in literatures [10–12]. However, the interest in utilization of natural fibers in biocomposites goes beyond their advantages for formulating new and mechanically improved materials. Interest is also driven by a global concern about the impact of plastics in the environment and a growing consciousness of the need for establishing a circular economy where residues like biomass and lignocellulosic can be valued and used as new raw material for industrial processes [13, 14]. In that regard it makes sense to use the agroforestry residues of extensive crops in a way that results in a neutral CO₂ process, like the fabrication of composites, instead of using them for energy production through combustion. An example of the potential of lignocellulosic materials is the region of Valle del Cauca in the South West of Colombia, which has a large influence of the sugarcane industry. It produces 80% of all Colombian sugar, and also it counts for 50% of all local agricultural production. This industry produces a lot of agroforestry residues, approximately 6 million tons of sugarcane bagasse a year [15]. The availability and low cost of this residue are thought as competitive advantages for the development of sustainable biocomposites in this region. That is the main reason behind of our resent research: the valorization of sugarcane residues by their use in natural fiber reinforced polymer composites (NFPC). In regard to the use of sugarcane bagasse, some studies have reported its use as reinforcement for polypropylene, polyester, recycled PET, PVC, HIPS, and HDPE and as agents and/or compatibilizing treatments such as aluminates and mercerization (NaOH treatment) and the use of ethylene and methyl acrylate as copolymers and benzyl chloride [16–19]. However, to the best of our knowledge, there have been no reports of the use of silanes as compatibilizing agents in sugarcane bagasse microfibers, in order to improve their adhesion to polymer matrices. In this chapter, polypropylene bagasse (PP bagasse) biocomposites prepared through extrusion, injection, and thermocompression molding will be evaluated. The morphology as well as the mechanical, thermal, and thermomechanical properties of the biocomposites will be investigated with the aim to understand the effect of the chemical treatments of the bagasse fibers on the polypropylene (PP) matrix properties.

2. Materials and methods

2.1. Materials

Sugarcane bagasse was obtained from a local sugar mill and kindly provided by Sucromiles S.A. Hexadecyltrimethoxysilane and sodium hydroxide were analytical-grade reagents from Aldrich (Wisconsin, USA). Absolute ethanol was a product from Merck (PA, USA). Polypropylene homopolymer 01H41 was obtained from Essentia (Cartagena, Colombia).

2.2. Preparation and characterization of sugarcane bagasse microfibers

Sugarcane as received was cleaned with distilled water in order to take off soil and residues from the lignocellulosic material. Clean bagasse was later dried at 60°C for 6 h until constant weight. Around 500 g of bagasse was then grounded using a Kinematica™ Polymix™ PX-MFC 90 D Lab mill drive and a sieve size of 200 µm. The sample was divided in three groups: one used as it was obtained after milling with no further treatment. A second group was treated with an aqueous solution of 8% NaOH using a 1:1 bagasse/solution ratio during 2 h, in order to remove lignin from the bagasse's surface. A third group of fibers were silanized after lignin removal. For silanization, a solution of 2×10^{-3} M of octadecyltrimethoxysilane in an 8:2 ethanol/water ratio as solvent was prepared. The pH of solution was kept at 3 using acetic acid. A time of 10 minutes was allowed for hydrolysis after addition of silane and before the solution was sprayed over bagasse fibers using a plastic spray bottle. Wet fibers were allowed to dry at 90°C for 24 h in a forced air oven. After drying, fibers were kept in plastic bags until used in the composition process with polypropylene.

Each group of fibers was characterized by thermal gravimetric analysis (TGA) using a nonre-active atmosphere (N₂ at 50 mL/min) from 25 to 650°C at a heating rate of 10°C/min using a TGA/DSC 2 STAR system, from Mettler Toledo. Surface structure of fibers was characterized by scanning electron microscopy (SEM), and chemical maps are also obtained by electron dispersed spectroscopy (EDS) using an ultra-high-resolution analytical FE-SEM SU-70 from Hitachi. All samples were sputtered with gold before analysis. Silicon content on fibers was quantified by flame atomic absorption spectrometry (FAAS). Around 0.5 g of fibers was calcinated at 550°C for 4 h in porcelain crucibles. After calcination each sample was treated with 2 mL of HF (48–50%) and 98 mL of H₂SO₄ 0.08 M. Samples were kept for 24 h in polypropylene containers for 24 h and then filtered. Quantification using Analyst 800 from Perkin Elmer was performed using a nitrous oxide/acetylene flame.

2.3. Preparation of the biocomposites

Biocomposites were compounded in a counter-rotating twin screw extruder Thermo Scientific HAAKE™ PolyLab. In all cases fibers were physically premixed with polypropylene pellets in a plastic bag using 20% of fiber in weight. About 500 g of fiber-polypropylene mix was introduced in the extruder at 70 rpm. A temperature gradient from 140 to 170°C from the feeder to the melting zone was used. The outcoming cord of composite from the extruder was pelletized using a rotating cutter which produced pellets of about 5 mm long.

After the pelletization process, the PP and PP-bagasse biocomposite samples were dried in an oven at 85°C followed by injection molding process at 180°C. A BOY XS (BOY Machines, Inc., USA) microinjection molding machine was used to prepare samples (3*12.7*60 mm) for flexural and impact tests. An injection pressure of 68 bar and a back pressure of 18 bar were used.

Also, sheets of the different samples were obtained using a hot-plate press and a forced water circulation cooling system (LabPro 400, Fontijne Presses). To shape the specimens, stainless steel molds were used. The molding was conducted at a temperature of 185°C, with a pressure of 50 kN and a 15 minute cycle. Finally, the sheets were demolded and adjusted to the required dimensions for DMA tests (1.7*12.7*60 mm) using a computer numerical control router. **Figure 1** shows the injected specimens of PP and a PP-bagasse biocomposite.



Figure 1. Injected specimens of PP and a PP-bagasse biocomposite.

2.4. Characterization of the biocomposites

2.4.1. Flexural properties

Three-point bending flexural tests were performed with an INSTRON universal testing machine model 3366 according to the ASTM D 790–17. The tests were carried out on bars of rectangular cross section at 23°C and at a rate of crosshead motion in 1.3 mm/min. This rate was determined based on the dimensions of the specimen. Also, the distance between the supports was 50 mm, and the tests were conducted up to 5% strain. All the results were taken as the average value of five samples.

2.4.2. Impact properties

The impact strength of PP and biocomposites were determined with an Izod Tinius Olsen impact pendulum equipped with a 4.53 N pendulum. Prior to the test, the materials were subjected to conditioning for 48 h at 50% relative humidity and a temperature of 25°C. The specimens were made following the standard ASTM D256, and the starting angle of the test was 55.80°. All the results were taken as the average value of five samples.

2.4.3. Thermal characterization

Differential scanning calorimeter (DSC) and TGA test of the neat PP and biocomposites were carried out using a TGA/DSC 2 STAR system, from Mettler Toledo. DSC tests were carried out under nitrogen atmosphere (N_2 at 50 mL/min) from 20 to 200°C at a scanning rate of 10°C/min, with a sample of 10 mg in aluminum pans. Melting temperatures (T_m) were determined from the first heating scans. TGA was carried out on 10 mg samples using a TA Q500 thermogravimeter at 10°C/min from 23 to 600°C under nitrogen flow. The thermal degradation temperatures considered were the onset of inflection (T_0) and the temperature of maximum weight loss rate (T_{max}).

2.4.4. Dynamic mechanical analysis

Polymers and composites have a different response to mechanical loads in comparison with other materials. They can be studied as materials that in some cases behave as elastic solids

and, in others, as viscous fluids. As such, its mechanical properties also depend on time, stress, and temperature. The present study of the viscoelastic performance was carried out in a DMA RSA-G2 with ACS-3 Air Chiller System. In order to identify the viscoelastic behavior of biocomposites, the following test modes were used:

2.4.4.1. Strain sweep tests

To begin the study of the viscoelastic response of biocomposites, the linear viscoelastic region for the PP matrix was identified. To find this region, strain sweeps were carried out at a defined temperature. The geometry used to perform these tests was three-point bending. A strain sweep test takes successive measurements with an increase in the strain. For these experiments, the RSA-G2 was programmed with a strain between 0.001 and 1%; the frequency was constant at 1 Hz. Measurements were made at 0, 30, and 60°C.

2.4.4.2. Temperature ramp tests

After finding the linear viscoelastic zone, temperature ramp tests were performed to observe the behavior of the PP matrix at different temperatures. These tests were performed between -60°C and 170°C, at 1 Hz, 3°C/min, and 0.01% of strain.

2.4.5. Morphology

Scanning electronic microscopy (SEM) of biocomposites was carried out on the cryogenic fracture surfaces of the specimens using a Quanta FEG 250 microscope operating at a voltage of 10 kV.

The samples were previously sputter-coated with gold to increase their electric conductivity. The cross-sectional diameters of the dispersed phase were measured using ImageJ 1.8v (Wayne Rasband, National institutes of health, USA). Determinations were performed in different areas of the SEM images.

2.4.6. Statistical analysis

Flexural and impact properties of the materials were subjected to analysis of variance (ANOVA), and the Tukey's test was applied at the 0.05 level of significance. All statistical analyses were performed using Minitab Statistical Software Release 12 (Pennsylvania, USA).

3. Results and discussion

3.1. Preparation of bagasse microfibers for biocomposite fabrication

In order to produce and tune a lignocellulosic material to improve the mechanical performance of natural fiber reinforced polymer composites (NFPC), it is very important to conceptualize adhesion as one of the most important factors to achieve such challenge [20, 21]. Adhesion on the polymer-fiber interface is said to follow one of the four common mechanisms: mechanical interlocking, electrostatic interactions, molecular entanglement, or chemical bonding [22]. Many commercial polymer-coupling additives like maleic and acrylate grafted thermoplastics work as adhesion enhancers in polyolefins by generating chemical bonds with the free

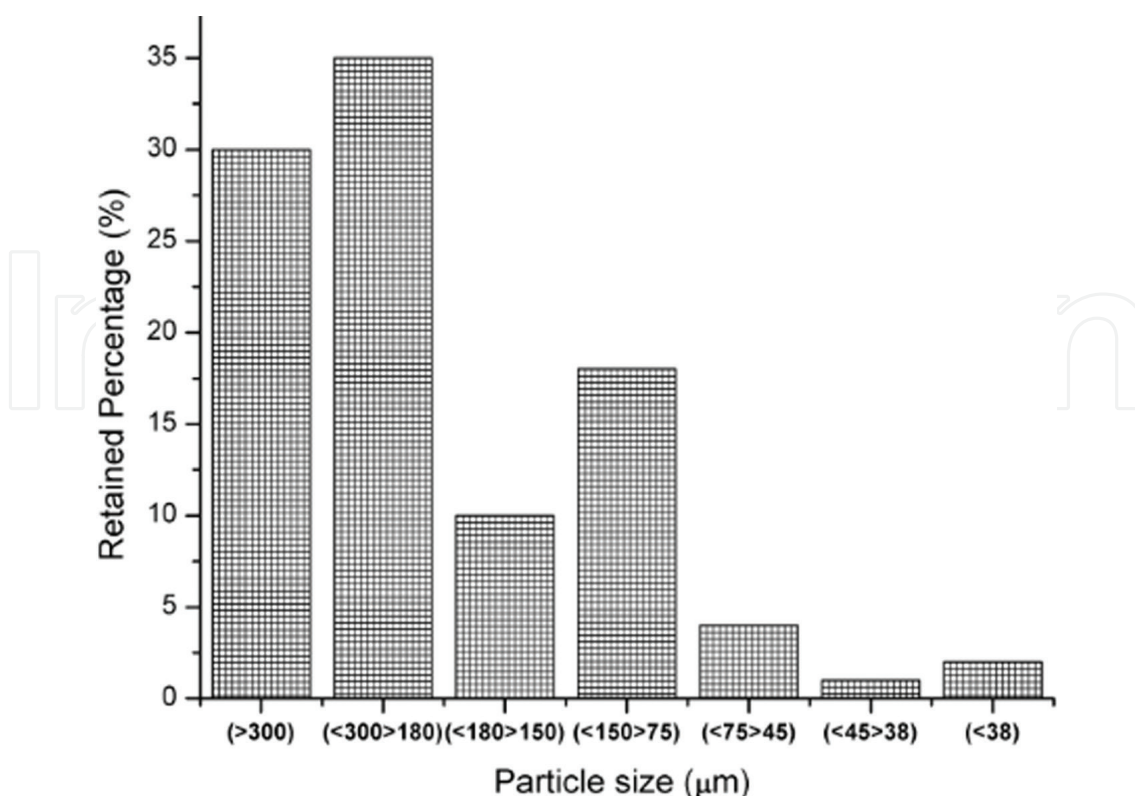


Figure 2. Granulometry of milled sugarcane fibers after lignin removal and silanization with hexadecyl triethoxysilane.

alcohol functionality on the fiber's cellulose [23]. In those aforementioned cases, the adhesion increases by conditioning the polymer to the fiber's surface. Instead, when silanes are used to increase adhesion, in the fiber's surface which is conditioned to interact with the olefin polymer matrix by promoting electrostatic interactions or chain molecular entanglement [24, 25].

When nonpolar silanes, like dodecyl, hexadecyl, or octadecyl triethoxysilanes, are used for fiber modification, there is a lowering effect of the fiber surface energy which increases compatibility with the matrix by matching the polarities [26]. A practical and quick way of estimating the surface energy of surfaces is by measuring the contact angle of the surface. However, in many NFPC applications, the size of the fibers used is in the range of micrometers, as shown in the granulometry in **Figure 2**, for the case of sugarcane bagasse fibers.

Measuring contact angle on rough surfaces, such as those formed for a bed of micro-sized fibers, can be challenging since the observed angle is the manifestation not just of the molecular interactions at the solid/liquid interphase but also of the microstructure of the surface (**Figure 3**).

This effect is counted by the model of Wenzel which predicts that if a molecularly hydrophobic surface is rough, the appearance is that of an even more hydrophobic surface [27, 28]. An interesting evidence of this phenomenon in particulate fibers is shown in **Figure 4**, where the contact angle of several groups of sugarcane bagasse fibers treated with solutions of variable silane concentrations appears almost invariant (between 122° and 129°), even though the absorbed amount of silane changes nearly in one order of magnitude (5.5×10^{-5} to 1.04×10^{-4} mol of silane per gram of fiber).

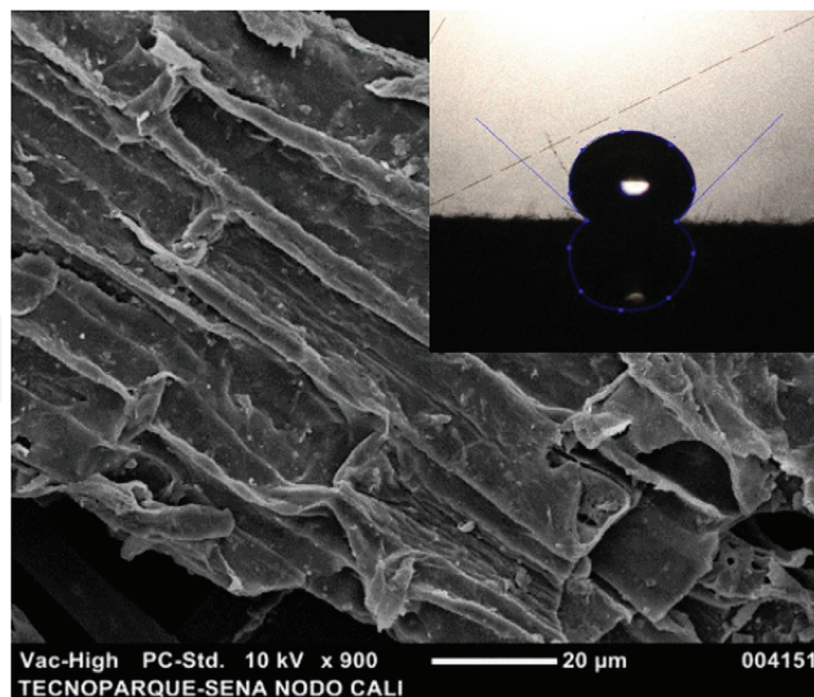


Figure 3. SEM photograph of a silanized sugarcane fiber. Inset shows the rough surface of a bed of fibers used to measure contact angle of the fibers.

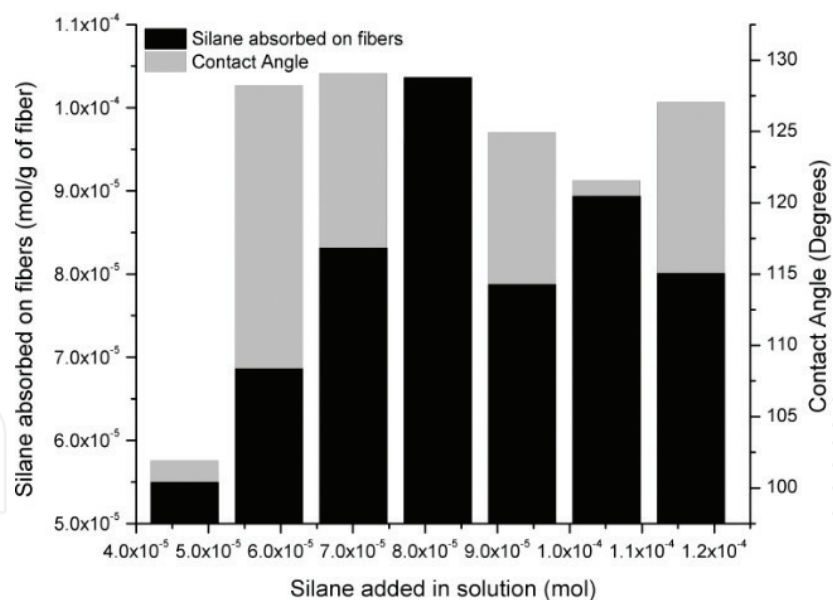


Figure 4. Effect of silane absorbed on microsized sugarcane bagasse fibers and their contact angle.

Another critical factor to achieve a good reinforcing material made of small natural fibers is the generation of anchoring points on the rough surface in order to produce enough silanization. Natural fibers in contrast with fiberglass, for example, do not have a well-defined geometry and instead lack of the advantage of having a highly energetic surface prone to react during silanization. Fiberglass has a surface populated with free hydroxyl groups from Si-OH functionality, but

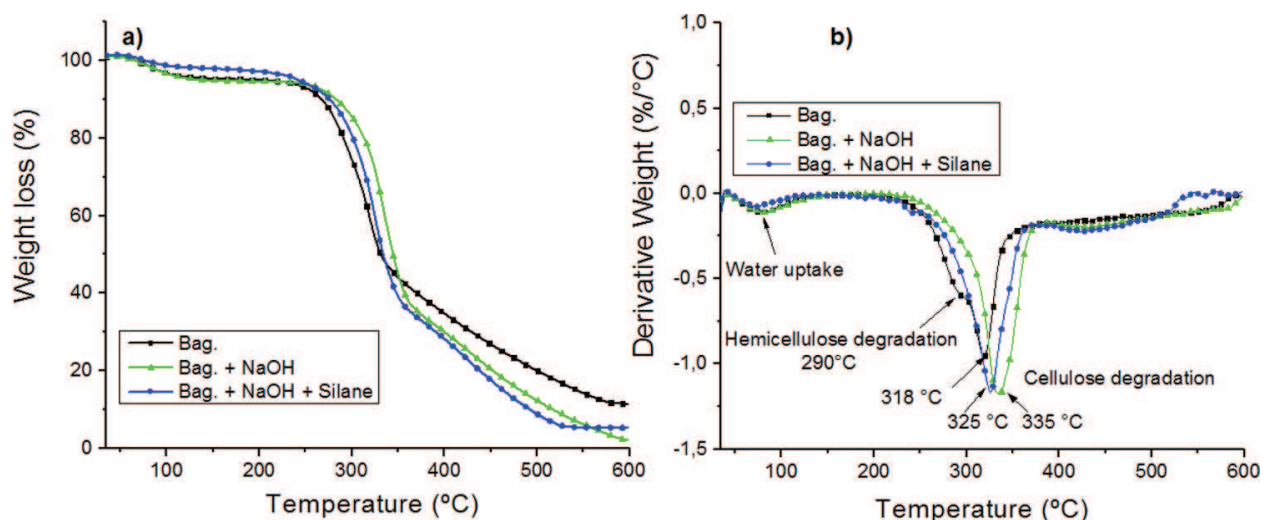


Figure 5. (a) TG and (b) DTG curves of bagasse fibers at heating rates of 10°C/min.

natural fibers are usually covered by a nonreactive lignin layer. That is why for natural fibers, the surface area that will react with silanes is determined by a good process of lignin removal, using alkaline or oxidative solutions, which will expose cellulose at the natural fiber's surface [29, 30].

The performance of the delignification treatment can be estimated from thermal gravimetric analysis (TGA) of fibers. **Figure 5** shows the TGA of sugarcane bagasse fibers before and after delignification with alkaline treatment and after silanization.

When a good delignification is carried out, fibers gain some thermal stability. As shown in **Figure 5**, the T_0 for sugarcane bagasse goes from 262 to 282°C when lignin has been removed. Also, as noted in the DTG, the typical signal of hemicellulose around 290°C disappears [31]. Furthermore, after most of lignin goes away, it is possible to observe a cleaner DTG signal with no shoulders that make evident the presence of residual compounds in the fibers. With only cellulose, the maximum degradation (T_{max}) in DTG occurs around 325°C. Silane presence also increases T_{max} to 335°C, mostly due to the formation of refractory siloxane network after silanization. Additionally, as observed in the TGA results, when surface modification by silanization with hydrophobic moieties has occurred, there is a clear decrease of water evaporation after 60°C, since fibers absorb less water when silanized. Changes in water uptake can go from 5 to 1%. This result indicates that silanization process reduces water absorption of the fibers and may give resistance against fungal decay [32].

Another factor that plays a role in the reinforcing ability of fibers is the distribution of silane on their surface. Few works have detailed how silane gets distributed in the rough surface of natural fibers. Using chemical maps from scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDS), it is possible to survey the surface and locate silicon at specific locations on the fiber [33]. **Figure 6** shows the chemical maps for oxygen and silicon, as an example of chemical mapping of silanized fibers.

From SEM-EDX spectra, the concentration of surface atoms can be estimated using the intensity of signals at the specific energies of each atom. In this case, sugarcane bagasse fibers modified with hexadecyltrimethoxysilane were interrogated for the content of oxygen, silicon, and carbon before and after silanization. **Figure 7** reviews the results. Spectra revealed

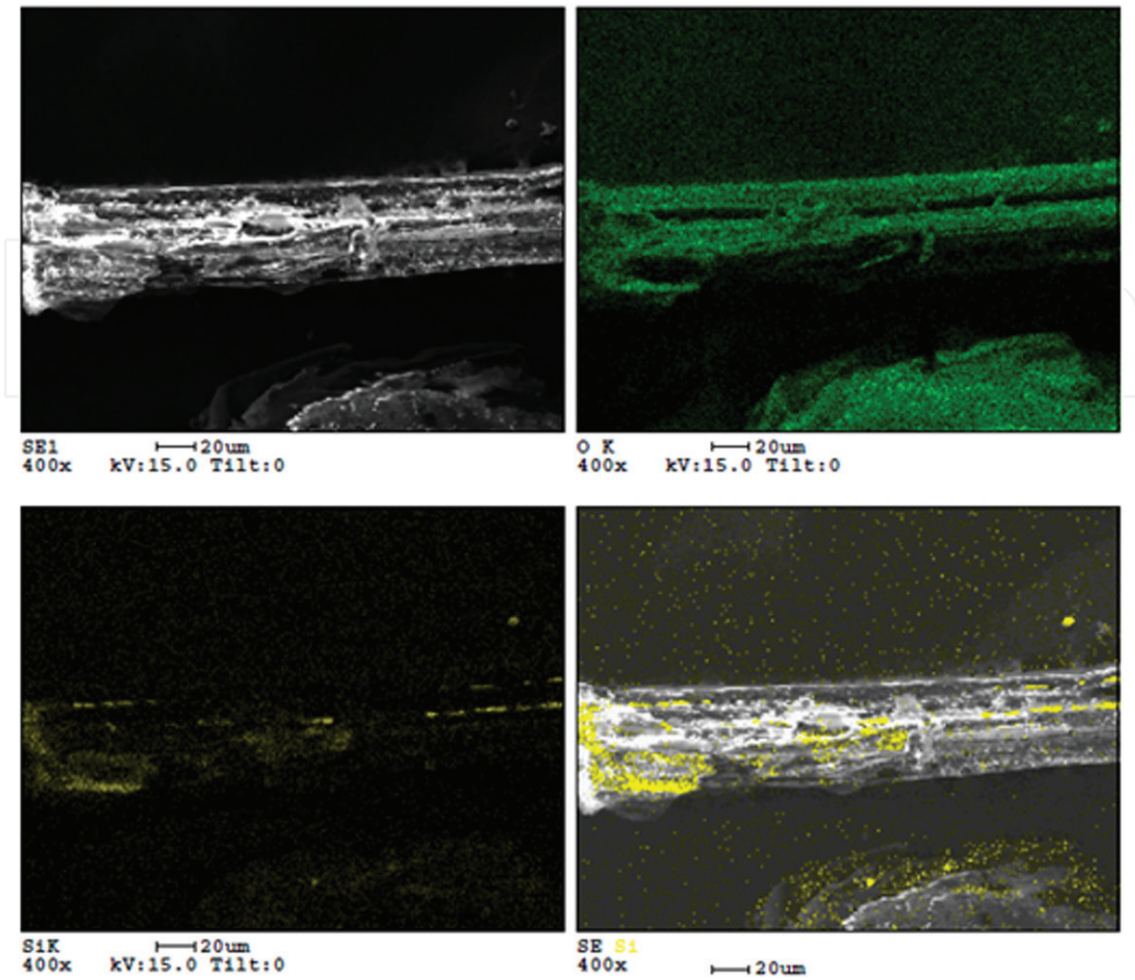


Figure 6. SEM-EDX chemical maps of sugarcane bagasse fiber treated with hexadecyltrimethoxysilane after delignification with NaOH 8%.

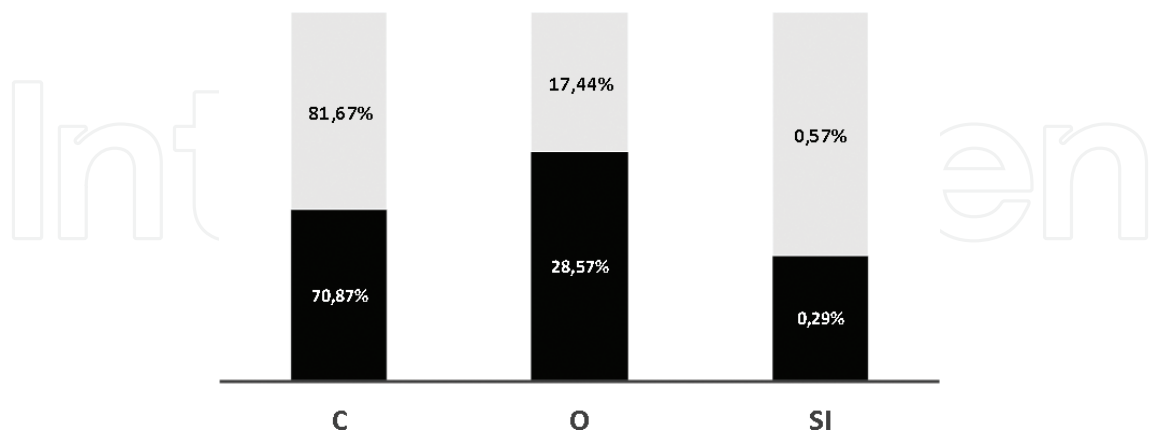


Figure 7. Percentage of total atomic content of carbon, oxygen, and silicon at fiber surface (black) and after (gray) silanization, measured by SEM-EDX.

that atomic oxygen content changed from 28.57 to 17.44%, carbon from 70.86 to 81.67%, and silicon from 0.29 to 0.57% before and after silanization, respectively. The variations in the atomic content are in agreement with the process performed. For example, the increment in

carbon content after silanization is due to the additional carbons brought to the surface by the long chains (C16) of hexadecyltrimethoxysilane. For oxygen instead, the surface atomic concentration becomes lowered since a not-significant amount of oxygen is added by silanes. Silicon, as expected, almost doubles his surface concentration.

In general, thermal, morphological, and chemical characterization of fibers is necessary when lignocellulosic materials are prepared as reinforcing fillers. The knowledge of important factors like the degree of lignin removal, distribution of silane, and hydrophobic character of fibers are very important to ensure that the material will behave successfully during compounding with polymeric matrices and then to obtain suitable mechanical properties of biocomposites.

3.2. Biocomposite characterization

3.2.1. Mechanical properties

The influence of bagasse fiber addition on the PP flexural and impact properties was evaluated. **Table 1** presents the values of the flexural modulus, flexural strength, and impact strength of the materials. Biocomposites showed different mechanical properties, indicating that the treatments affect the fiber-matrix interaction.

The results show that bagasse fiber incorporation induces a significant improvement of flexural properties of PP. For PP-bagasse and PP-Bag+NaOH biocomposite flexural modulus (FM) increased 60 and 42%, respectively. On the same way, flexural strength (FS) reached improvements of 20 and 8% compared to neat PP. For PP-Bag+NaOH+Silane, FM was enhanced 16%, respectively, in comparison with PP. However, the FS value was not significantly different ($p \geq 0.05$). Similar results were reported by Cerqueira et al. [34] when they studied the morphology and mechanical properties of PP-bagasse biocomposites. The authors reported that biocomposites present higher FM and FS values in comparison with neat PP and suggested a good interaction under the compressive stresses developed in part of the transverse section of the biocomposite specimens during bending.

On the other hand, the impact tests did not show significant differences between the PP matrix and the biocomposites PP bagasse and PP-Bag+NaOH. However, for PP-Bag+NaOH+Silane an

Sample	Impact and flexural properties*		
	Flexural properties		Impact properties
	Modulus (MPa)	Strength (MPa)	Impact strength (kJ/m ²)
PP	1296 ± 70 ^a	40.0 ± 0.7 ^a	4.4 ± 0.5 ^a
PP-Bag	2069 ± 30 ^b	48.0 ± 1.1 ^b	4.2 ± 0.2 ^a
PP-Bag+NaOH	1847 ± 114 ^c	43.3 ± 0.5 ^c	5.1 ± 0.5 ^a
PP-Bag+NaOH+Silane	1505 ± 94 ^d	38.6 ± 1.9 ^a	6.2 ± 0.1 ^b

Different letters (a–d) in the same column indicate significant differences ($p < 0.05$).

*Mean of five replications ± standard deviation.

Table 1. Flexural and impact properties of PP and PP-bagasse biocomposites.

increase of 40% was observed. This result shows that silanization increases the capacity of PP to absorb energy. This phenomenon can be explained by a possible energy absorption promoted by fracture mechanisms, which involve detachment, slippage, and fragmentation of the fiber. These mechanisms do not occur in neat PP and PP biocomposites without silanization.

3.2.2. Dynamic mechanical analysis

3.2.2.1. Strain sweep tests

Figure 8 shows the results of the strain sweep tests of the PP matrix. Images of the PP specimen are included at a strain of 0.01% (linear region) and 0.6% which corresponds to the non-linear zone. In this zone it is observed that the specimen has been highly deformed. From these results a strain of 0.01% was used for subsequent temperature ramp tests.

3.2.2.2. Temperature ramp tests

Figure 9 shows the thermograms obtained in the DMA for the PP matrix and its biocomposites. In these graphs the values of the storage modulus (E'), loss modulus (E''), and tan delta are shown. Neat PP tan delta plot shows two relaxations located near 6°C (β relaxation or T_g) and 60°C (α relaxation) [35]. It is also observed that the values of E' are temperature dependent. At 25°C the value of E' is 2708 MPa, while at 75°C, this value is 1199 MPa, which represents a decrease of 55%.

In the tan delta plot of the biocomposite PP-Bag (**Figure 10**), a T_g of 5.3°C is observed, while the α relaxation increased 17.5°C compared to the neat PP. Also, E' values at 25°C is 2454 MPa,

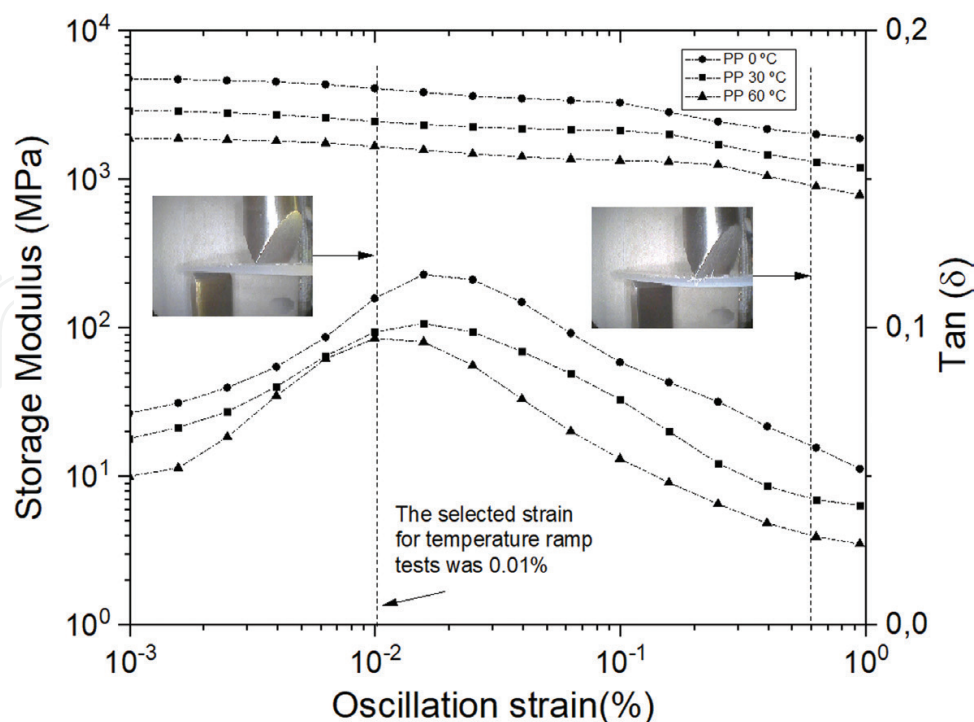


Figure 8. Strain sweep test curves for neat PP at 0, 30, and 60°C.

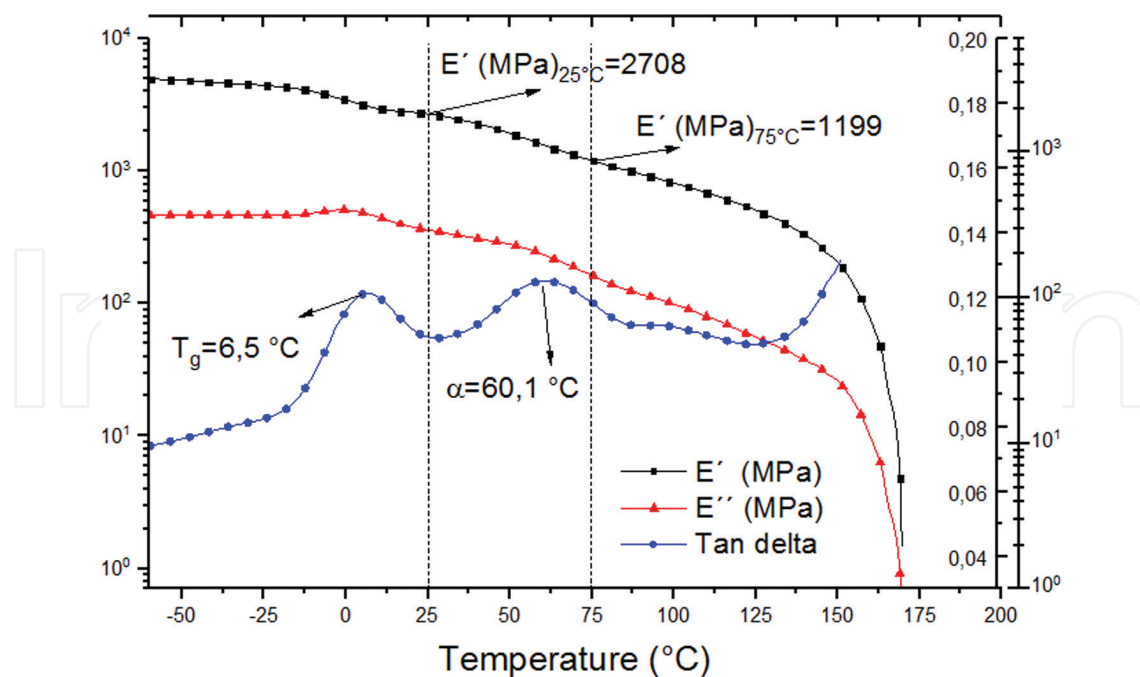


Figure 9. Dynamic mechanical analysis (DMA) curves of neat PP.

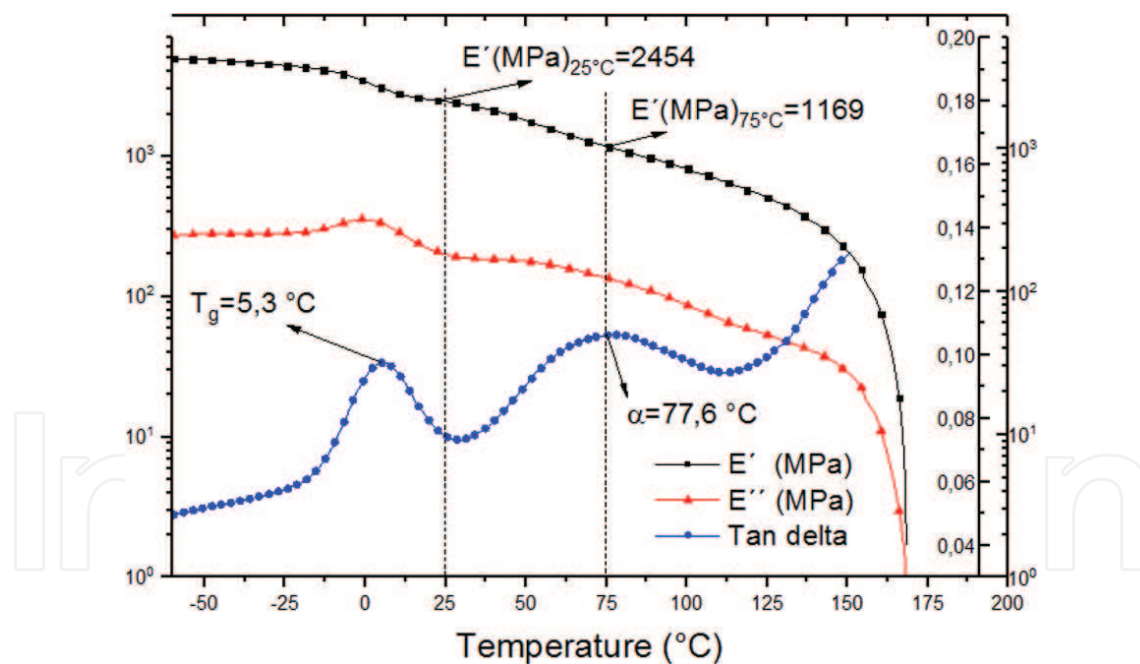


Figure 10. Dynamic mechanical analysis (DMA) curves of PP-Bag biocomposite.

while at 75°C , this value is 1169 MPa . E' values' decrease in this temperature range was 52%. This result shows that the addition of bagasse fiber improves the stability of the storage modulus of the PP matrix with the temperature. The increase in the value of α relaxation and the stability of E' with the temperature was also observed in biocomposites PP-Bag + NaOH and PP-Bag + NaOH+Silanes (Figures 11 and 12).

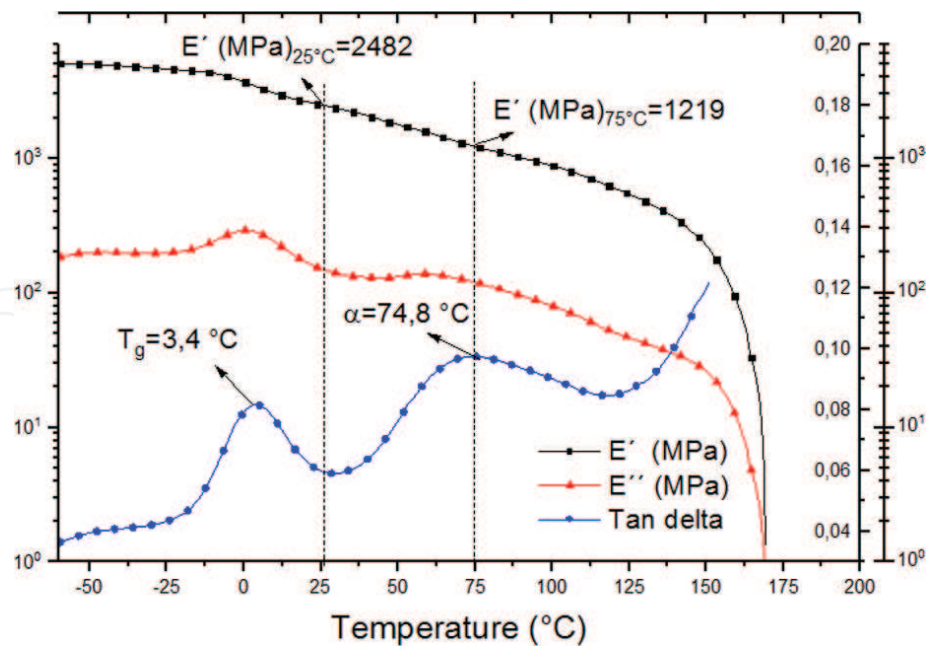


Figure 11. Dynamic mechanical analysis (DMA) curves of PP-Bag + NaOH biocomposite.

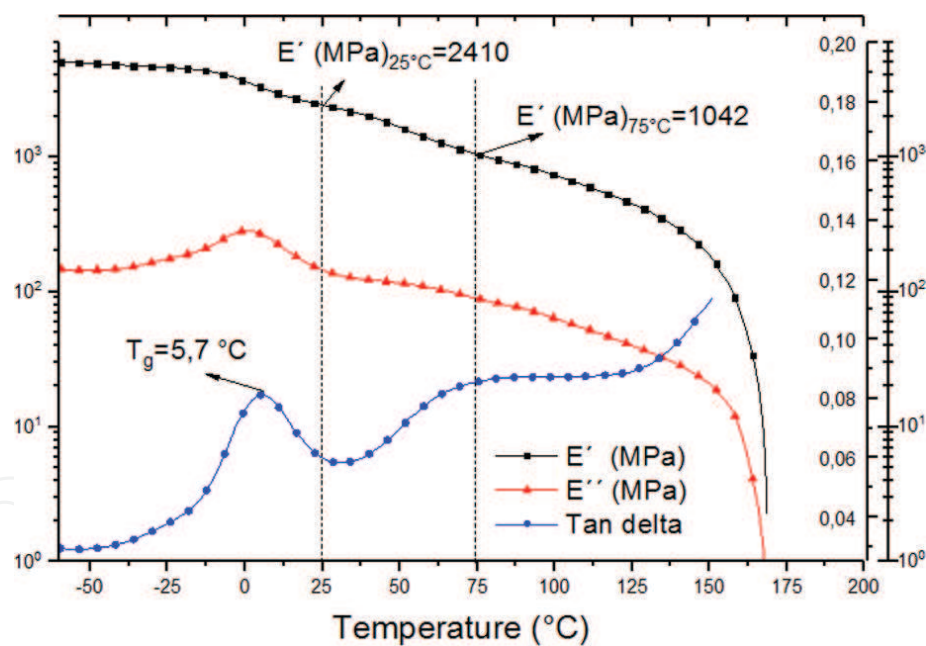


Figure 12. Dynamic mechanical analysis (DMA) curves of PP-Bag + NaOH+Silane biocomposite.

Figure 13 shows the summary of the temperature sweep tests for biocomposites. The tan delta graphics show that there are no significant changes in the T_g of the biocomposites compared to the PP matrix. The values of T_g range between 3.7°C and 6.5°C . Also, these graphs show a reinforcing effect in the PP-bag biocomposite. Tan delta values varied 19.8% compared to the PP matrix. In the case of biocomposite PP-Bag + NaOH, this variation was 32.64% while in the biocomposite PP-Bag + NaOH+ Silane was 32.95%.

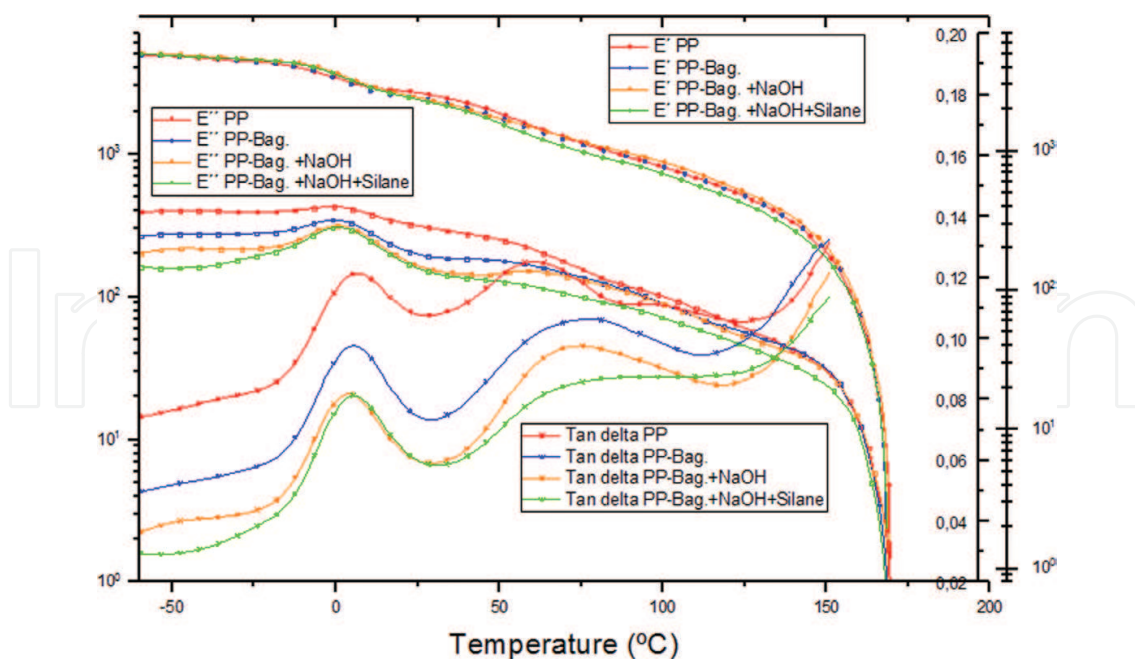


Figure 13. Dynamic mechanical analysis (DMA) curves of neat PP and its composites.

With temperature increase, a second peak is observed around 60°C for neat PP. This peak can be related to an alpha transition. In the case of biocomposites, this alpha transition can be spotted at higher temperatures. This suggests that the service temperature of the biocomposites with alkaline and silanized treatments would allow a better performance of the material. In this experiment observed that the addition of silane to bagasse does not generate an improvement in the viscoelastic properties compared to the alkalization treatment. It is emphasized that the alkalization treatment generates an improvement against the damping. This improvement can be positive for biocomposite applications that require an enhanced mechanical performance against stresses produced by bending loads.

3.2.3. Thermal characterization

3.2.3.1. Differential scanning calorimetry (DSC)

The first heating runs of PP and PP-bagasse biocomposite were shown in **Figure 14**. Both samples exhibit an endothermic peak between 163 and 165°C corresponding to the melting of the PP matrix. These results indicate that the addition of the bagasse fibers does not disturb the melting processes of the PP matrix.

3.2.3.2. Thermogravimetric analysis (TGA)

TG and DTG curves for PP and PP-bagasse biocomposites are shown in **Figure 15a and b**, respectively. Neat PP degradation occurs in a single-step process with an onset temperature (T_o) located at 371°C and a T_{max} of 449°C. Regarding biocomposites, TG and DTG show that degradation occurs in a two-step process. The first degradation step is associated with the

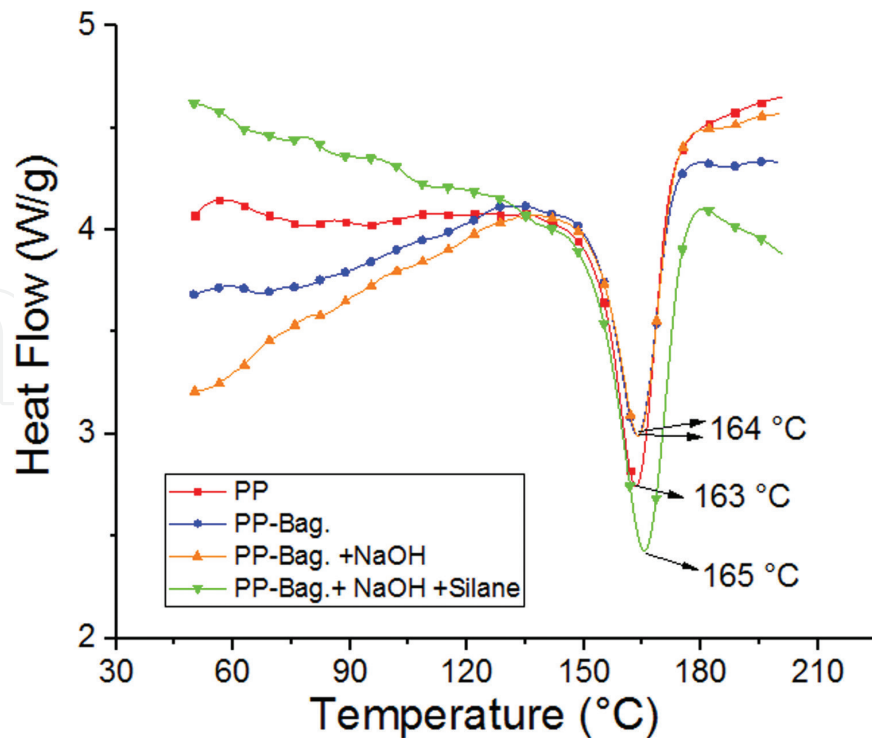


Figure 14. First heating DSC curves for neat PP and PP-bagasse biocomposites.

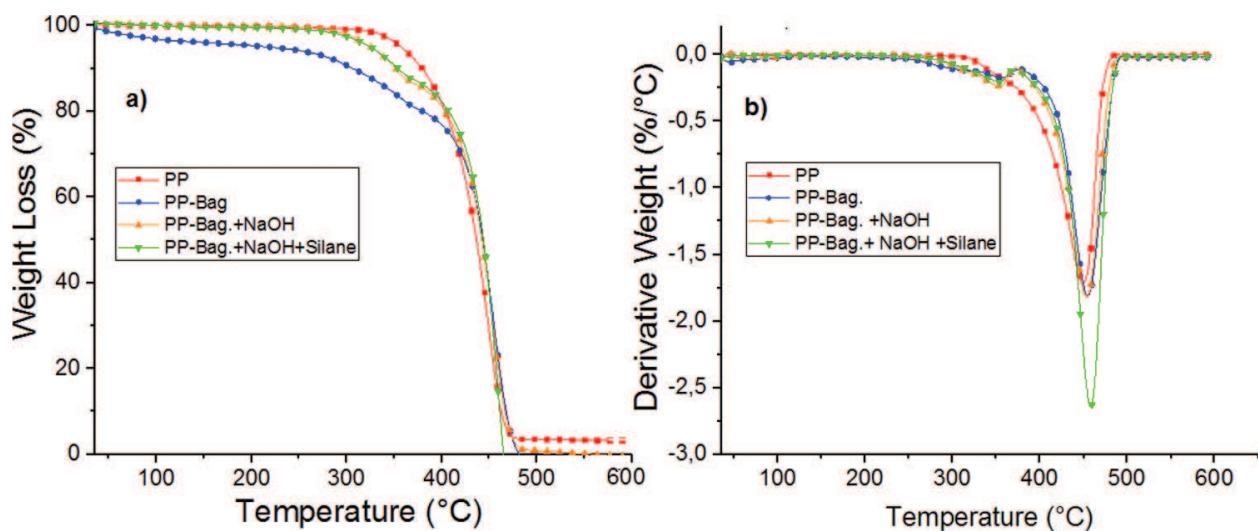


Figure 15. (a) TG and (b) DTG curves of neat PP and PP-bagasse biocomposites.

decomposition of fiber constituents with a T_o located between 264 and 311°C for neat bagasse and silane-modified bagasse, respectively. This result indicates that chemical treatments improve the thermal stability of bagasse fibers.

The second degradation step corresponds to the decomposition of PP matrix. As shown in **Table 2**, T_o increases between 51 and 53°C. Also, T_{max} increase between 4 and 9°C in comparison

Sample	Degradation stage	T ₀ (°C)	T _{max} (°C)
PP	1	371	449
PP-Bag	1	264	353
	2	423	455
PP-Bag + NaOH	1	310	355
	2	422	453
PP-Bag + NaOH + Silane	1	311	355
	2	424	458

To: onset of inflection of each stage in TG curves.
T_{max}: peak of the maximum degradation rate in DTG curves.

Table 2. Thermal degradation data of the samples at 10°C/min in nitrogen atmosphere.

to neat PP. This increment in the thermal stability of the biocomposites has been previously observed in different studies [36, 37], indicating that the incorporation of fibers in the material induces spherulite nucleation points, increasing the crystallinity of the polymer and improving its thermal properties.

3.3. Morphology

Figure 16 shows SEM images of fractured surfaces from PP-Bag and PP-Bag+NaOH+Silane biocomposites. Gaps between the bagasse fibers and the surrounding PP matrix can be clearly observed in **Figure 16a**, which indicates a poor interfacial adhesion between the PP matrix and the bagasse fibers [38]. For **Figure 16b**, with the chemical treatments, we can see that the gaps between bagasse and PP were reduced significantly and exhibited improved interface for the composite. This result confirms that chemical treatments expose the bagasse fibers and provided links between the cellulosic fibers and the surrounding polymer long chains, which improved the interfacial property of the hydrophobic PP matrix and the hydrophilic bagasse.

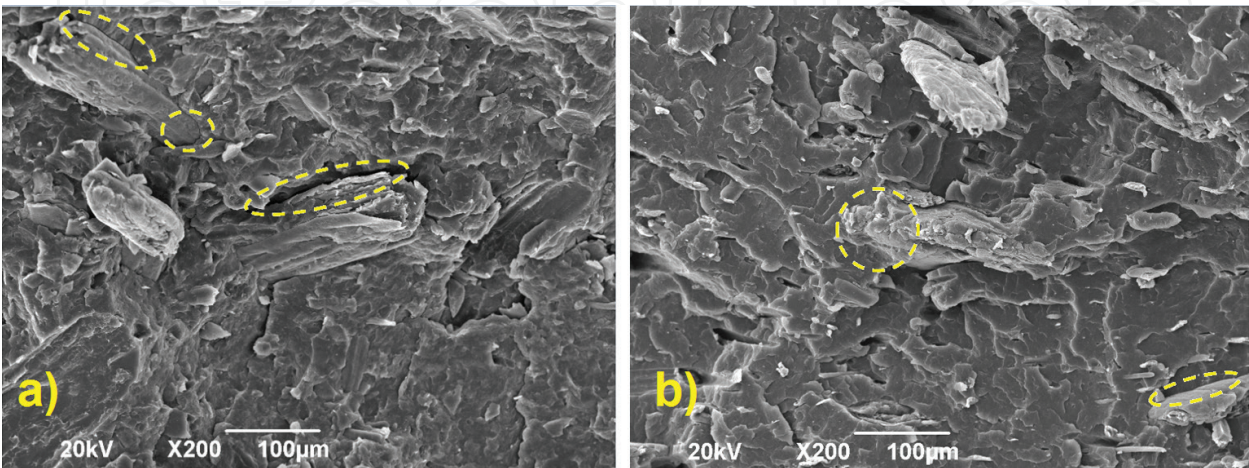


Figure 16. SEM pictures for a) PP-Bagasse and b) PP-Bag + NaOH+Silane biocomposites.

4. Conclusions

The chemical composition and thermal behavior of neat and chemically modified sugar bagasse fibers were studied. The biocomposites of bagasse fiber incorporated into a PP matrix were prepared by a melt-extrusion, injection, and thermocompression processes. The effects of bagasse fibers and chemical modification on the properties of the biocomposites were explored. Flexural characterization showed that bagasse fiber incorporation induces a significant improvement of flexural properties of PP. Also, the impact tests showed that the addition of silanized bagasse increases the capacity of PP to absorb energy. The DMA experiments show that bagasse fiber addition improves the maximum service temperature of the PP matrix. It was also observed that silanization process didn't improve the viscoelastic properties compared to the alkalization treatment. However, the alkalization treatment generates an improvement against the damping of the PP matrix. Thermal studies show that bagasse fiber addition did not disturb the melting process and improves the thermal stability of the PP matrix. This study offers an environmentally friendly alternative for utilizing waste bagasse fiber generated by the sugar industry for the production of biocomposites.

Acknowledgements

The authors acknowledge the Autónoma de Occidente University, Cali-Colombia, for the technical and financial support; the nanocharacterization center of Virginia Commonwealth University, Virginia-United States, for EDX and SEM spectra; Santiago de Cali University, Cali-Colombia, for its support in the use of FAAS; Servicio Nacional de aprendizaje (SENA), Cali-Colombia, for the financial support through the System of Research, Technological Development and Innovation (SENNOVA). In addition, we wish to thank the company "Sucromiles" Colombia, for providing the sugarcane bagasse.

Conflict of interest

The authors of this manuscript declare that they do not hold any conflicts of interest that might have any bearing on research reported in their submitted manuscript.

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