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Processability and Mechanical Properties of Spent Coffee Ground (SCG) and Polypropylene Biocomposites

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Processability and Mechanical Properties of Spent Coffee Ground (SCG) and Polypropylene Biocomposites

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Abstract: The circular economy encourages optimizing use of plastics, waste reduction, sustainable materials, and processing of plastic products. In this framework, the use of agricultural waste materials promotes waste reduction and eco-design in plastic product manufacturing. This study researched the preparation of an isotatic polypropylene (PP) matrix (MFI 50 grade) with spent coffee grounds (SCG) and various commercial additives. The biocomposites were analyzed to evaluate their mechanical properties and processability. PP and SCG composites were synthesized with 30% SCG content with maleic anhydride grafted polypropylene (PP-g-MA), stearic acid and epoxidized oil as compatibilizers. The study found that polypropylene grafted with maleic anhydride (PP-g-MA) as a compatibilizer improves SCG dispersion, enhancing processing stability. Epoxidized oil (EO) and stearic acid (SA) can also function as lubricants that significantly improve composite processability by decreasing specific energy and shear viscosity. The processability properties were accessed using a torque rheometer. A tensile test showed that while SCG addition decreases mechanical strength, PP-g-MA improves interfacial adhesion, and EO and SA increase flexibility by reducing brittleness.

Keywords: Biocomposites, Compatibilizers, Processability, Circular Economy

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Introduction

Finding environmentally friendly and sustainable materials is becoming essential in our society. One potential solution is incorporating agricultural and industrial waste into polymeric matrices [1]. Coffee is a widely consumed agricultural product in Ecuador and coffee drinks have become a trendy beverage. However, the preparation of coffee drinks generates organic waste. These wastes contain components that make them attractive as reinforcements in polymer matrix composites. They contain polyphenols, which are compounds that provide antioxidant properties that help protect materials from degradation. In addition, the presence of components such as cellulose, hemicellulose, lignin, and fatty acids improves the mechanical properties of the biocomposite [2].

Developing biocomposites based on thermoplastic matrices reinforced with natural fibers faces several problems due to the low compatibility and processability as a result of the hydrophobic matrix and hydrophilic reinforcement, affecting the final product's performance [3]. Garcia et al. [4] increased impact energy in the biocomposites to mitigate these drawbacks. Fuqua et al. [4] incorporated 5% by weight of PP-gMA into a corn fiber-reinforced polypropylene matrix, showing that the elastic modulus and strength of the biocomposites were improved compared to incompatible biocomposites. Regarding coffee residues, Leal et al. [5] incorporated ground coffee husk (GCH) in proportions of 20, 30, and 40% by weight to a PP and used PP-g-MA as a compatibilizer at 10% by weight relative to GCH. Relative to pure PP, the composite with 40% GCH increased flexural strength, flexural modulus, tensile modulus, and thermal distortion temperature. Similar findings in thermal, mechanical, and other physical properties occurred due to improved interface interaction between the maleic anhydride from PP-g-MA and the hydrophilic reinforcement particles [3,6]. Most studies examine the relationship between the formulation compound and the physical properties of the SGC biocomposite [7,8]. The processability and energy consumption of polymer composites reinforced with coffee wells are very relevant from the industrial perspective, especially those using polypropylene grafted with maleic anhydride as a compatibilizer. This area of research offers enormous potential for developing low-energy processing, sustainable materials, which require exploration to optimize their properties and processing energy efficiency.

In this study, a coffee-reinforced polypropylene thermoplastic composite material is investigated by evaluating the incorporation of three additives: polypropylene grafted with maleic anhydride (PP-g-MA), stearic acid (SA), and epoxidized oil (EO). The objective is to analyze how these additives interfere with the properties of the composite material. The interaction of the additives is evaluated in terms of the mechanical properties through tensile tests and the processability of the material.

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Methodology

Materials

SCG used as reinforcements were supplied by Sweet & Coffee, a national coffee shop. Polypropylene (PP) with melt flow index (MFI) of 50 g/10min (230°C/2,16 kg) and the maleic anhydride grafted polypropylene (PP-g-MA) with MFI of 22.4 g/10min a density of 0.904 g·cm^{-3}, epoxidized oil (EO) with a density of 0.995 g·cm^{-3} and viscosity of 450 cP were kindly donated by Plasticos Industrial CA (PICA), and stearic acid (SA) with an acid value of 209-212 mgKOH/g was supplied by Dua Kuda, Indonesia.

Mixture Preparation

SCG was dried at 60°C for about 24 hours. Each component was weighed using a digital balance, following the formulations outlined in Table 1. Subsequently, the components were blended in a Brabender torque rheometer at 60 rpm and a temperature of 180°C for 10 minutes. The PP, PP-g-MA, EO, and SA were introduced initially, and the SCG was incorporated after 2 minutes.

Table 1. PP/SCG formulations.

	PP (%)	SCG (%)	PP-g-MA (%)	EO (%)	SA(%)
PP	100	—	—	—	—
SCG30	70	30	—	—	—
SCG30/PP-g-MA	65	30	5	—	—
SCG30/EO/SA	65	30	—	—	5
SCG30/PP-g-MA/EO/SA	60	10	—	5	5

Biocomposite Preparation

The mixtures obtained from the torque rheometer were pelletized using a plastic cutter. The pelletized material was placed inside a mold between the plates of a hydraulic press set to 180°C while maintaining a pressure of 0 psi for melting. Subsequently, a venting process was conducted, consisting of raising the pressure from 0 to 1500 psi and rapidly returning to 0 psi, repeated 10 times. The pressure was then raised to 1500 psi for 5 minutes and then increased to 2000 psi for another 5 minutes. Finally, the samples were cooled to room temperature and de-molded.

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Characterization and Evaluation

Torque Rheometry

After processing in the torque rheometer, the torque vs. time curves were obtained using the Mixer Program for Windows Version 4.9.8 (WinMix) and BRABENDER® Data Correlation Version 4.0.6 software. The specific energy consumed in the processing of each compound, E (kWh/kg), and the viscosity have been successfully obtained previously [9,10].

Mechanical Strength

The test for determining the tensile properties was performed according to ASTM D638 on a Shimadzu AG-IS 10 kN universal testing machine. The test speed was 5 $mm \cdot min^{-1}$ under ambient conditions of 23°C.

Results and Discussion

Figure 1 illustrates the polymer composite behavior of mechanical energy and torque proposed in this study, simulating the twin screw process. Figure 1(b) shows the torque rheometer as a function of time. This graph illustrates how the torque is strongly related to the composite formulation. When the amount of PP was decreased in the formulation towards the biocomposite, the loading torque was shifted from about 30 N.m to a range of 5-10 Nm. This behavior is due to the apparent filling degree in the chamber, observed previously in neat polymers and composites [9]. The increase in torque and energy consumption in this process can be attributed to the higher solids content and particle agglomeration, which disturbs the movement of the PP chains and increases the flow resistance [12]. However, the epoxidized oil and stearic acid consistently decrease the torque after the feeding time. The effect of these low molecular weight additives diminished the loading torque and torque after this feeding time. It has been observed that the presence of a broad molecular weight of polymer decreases the loading torque and the viscosity [12]. When the SCG is added to the PP/additives mixture, the torque increases due to the loading of the SCG. Then, the mixture melts, which significantly influences the torque required for blending and the overall processability of the composite. The torque for pure PP and PP/SCG stabilized at 2.43 N.m and 5.32 Nm, respectively. The PP-gMA significantly stabilizes the melting mixture at earlier times (4.32 min) compared to other additives (5.30 and 5.56). PP-g-MA has a remarkable ability to be a compatibilizer and stabilize the extrusion process, as has been widely observed [13]. Also, the SCG is rich in phenolic compounds [14], which can potentially protect PP and SGS degradation during processing. The good affinity and processability characteristics of PP-g-MA in the PP/SCG blend could be inferred from a smooth and horizontal flat torque during the stabilized zone in a similar approach as observed in the neat PP.

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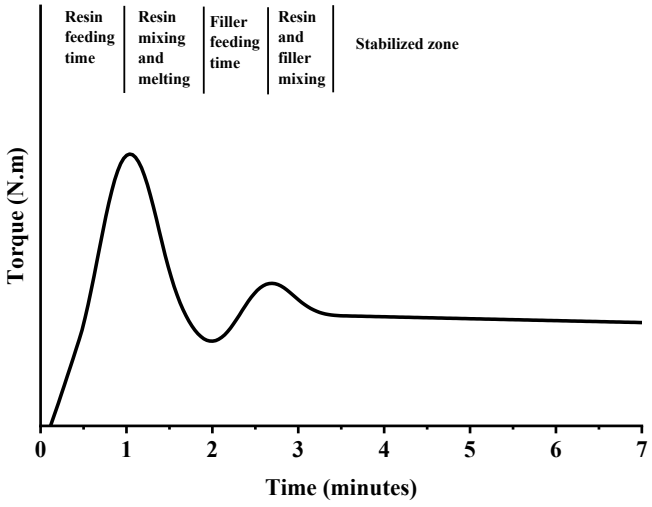
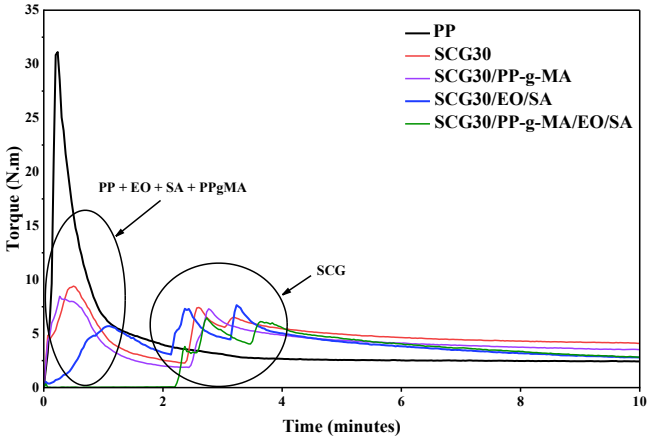


(a)



(b)

Figure 1. (a) Torque vs. Time for this research, adapted and modified from [11] and (b) Torque vs Time curves of compounds of coffee and compatibilizer additives.

In addition, EO and SA could act as lubricants; they could reduce the shear friction of the melt blending, and then the temperature and viscosity would decrease consistently. Figure 2(a) shows that EO/SA has the lowest viscosity and temperature for about 513,13 Pa.S and 182.23 C, respectively. However, Figure 1(b) shows that the ES and SA mixtures are still unstabilized at 10 minutes. For this reason, the PP-g-MA could help keep the melting quality during processing in this biocomposite. In general, it is observed that the temperature and the torque at 10 minutes are related to the viscosity and specific energy of the PP and biocomposite, so these results give a potential overview for the industrial scale process.

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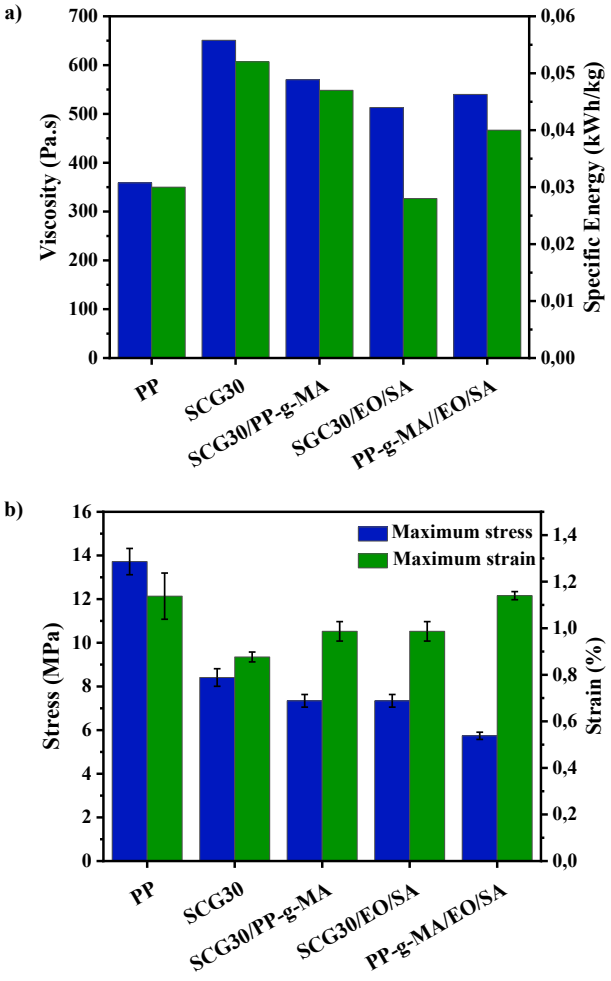

Figure 2. Results of (a) viscosity and specific energy (b) mechanical strength of the composites.

Figure 2(b) shows the maximum stress and strain properties of various PP/SCG composites, demonstrating the significant impact of SCG and different additives on these mechanical properties. A mixture of polyolefins and incompatible agro-industrial wastes generally produces poor mechanical properties [8,9]. Adding SCG to PP causes a substantial decrease in the maximum tensile stress, from about 14 MPa for pure PP to about 7 MPa for the SCG30 composite. This decrease indicates poor interfacial adhesion between the SCG fibers and the polymer matrix. It is also due to the low mechanical strength of voids and porosities, which give rise to significant stress concentration zones in composite materials [15].

On the contrary, the addition of PP-g-MA improves the strain of the biocomposite due to a slight improvement in the interfacial adhesion between the SGC and the polypropylene matrix, as observed in other polymer fiber biocomposites [16,17]. These results suggest that the compatibilizing agent promotes chemical interactions among the hydroxyl (OH-) cellulose, hemicellulose and lignin groups from coffee residues and the ester groups of PP-g-MA [18]. Using EO and SA as additives

further reduces the strength, with the SCG30/EO/SA composite showing maximum stress of 7.34 MPa. These additives significantly increase the strain, improving flexibility with values like neat PP. Therefore, the appropriate compatibilization and plasticizer effect plays an essential role in developing tailored mechanical properties of the biocomposite.

Conclusion

SCG increased the viscosity and torque at extrusion shear rates, as observed in the stationary torque rheometer. The polypropylene grafted with maleic anhydride (PP-g-MA), EO, and SA increases the feasibility of applying the extrusion process to this family of polyolefins SCG biocomposites. The PP-g-MA reduced by about 10-12% the torque, specific energy consumption, and viscosity from PP/SGC values, thus improving flow properties and processing stability. In addition, using EO and SA as lubricants significantly improves processability by reducing energy consumption and viscosity. Still, the melting processes were not stabilized after 10 minutes with EA/SA. While adding SCG decreases stress and strain, PP-g-MA slightly improves interfacial adhesion, and EO/SA mainly increases the flexibility and strain in the biocomposite formulations. This study gives an overview of agro-industrial waste polymer biocomposite processing and mechanical properties and puts forward an attractive industrial scale to be researched in this biocomposite family.

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