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Analysis of processing and environmental impact of polymer compounds reinforced with banana fiber in an injection molding process

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ABSTRACT

The global consumption of thermoplastic materials of fossil origin continues to grow, generating high environmental impacts mainly due to the energy consumed during their production and processing. The use of natural materials, such as banana fiber (BF), present a sustainable alternative for the gradual replacement of these thermoplastic materials, potentially reducing the environmental impact and improving their mechanical performance. This work presents the development of HDPE compounds reinforced with BF for injection molding of components with lower environmental impact. To this end, the processing and treatment of the banana pseudostem fiber have been analyzed, and compounds with fiber percentages of up to 20 wt %, with and without chemical treatment, have been developed and characterized thermal and mechanically. Finally, thickness optimizations of a case study component have been carried out through finite element simulation, with fiber percentages up to 30 wt %, maintaining the stiffness of the original HDPE component. A Life Cycle Assessment was also carried out to assess the influence of the different processing scenarios. The results showed, on the one hand, that the fibers without chemical treatment and with mechanical combing allow improvements in the mechanical properties of HDPE compounds similar to those obtained with chemically treated fibers but considerably reducing the impacts due to the suppression of the fiber treatment (chemical products, subsequent drying, etc.). On the other hand, the environmental impact analysis showed that compounds with percentages of untreated fiber greater than 20 wt % reduce the impact of the components produced compared to pure HDPE. Finally, the incorporation of the BF also allowed the design optimization of the study component, reducing its thickness but maintaining the same original stiffness, further improving its environmental impact.

1. Introduction

The fight against climate change and sustainable development is today's society's two major environmental goals. With annual emissions of 3132 million tons of CO_2 equivalent in 2019 (European Environment Agency, 2021), Europe targets a 55% reduction in emissions by 2030 and a climate-neutral economy in 2050 (European Parliament, 2021), which allows energy decarbonization (responsible for more than 75% of greenhouse gas emissions in Europe). Specifically, in 2020, European manufacturing industries consumed 24% of the total energy produced (Ritchie, 2020). Therefore, the search for more efficient and sustainable manufacturing processes (di Foggia, 2021; Dolge et al., 2021) and the development of more efficient products have made it possible to improve sustainability, increasing industries' competitiveness and commercial results (di Foggia, 2021). However, in many cases, it is not enough to offset the increase in energy consumption due to the production growth (Dolge et al., 2021).

Thermoplastic materials are widely used in industry to manufacture all kinds of products. Polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) comprise almost 60% of European production, which reached 57.9 million tons in 2019, -6.3% compared to 2018 (PlasticsEurope, 2020). However, global production does not stop growing, with 368 million tons in 2019 (+2.5% compared to 2018) (PlasticsEurope, 2020), producing a direct impact on global CO_2

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emissions (Oktavilia et al., 2020) estimated at 850 million tons of CO_2 in 2019 (both from production and incineration) (Arkin et al., 2019). This phase of obtaining thermoplastics can cause more than 50% of the product's total impact, followed by the manufacturing process and its transport (Choi et al., 2018; Dormer et al., 2013). For this reason, optimizing products manufactured with thermoplastics from the design stage is crucial since this phase can condition up to 80% of their impacts (How to Do Eco, 2000). The incorporation of lower impact materials, the introduction of lightning agents, or the optimization of the product with reinforcements are solutions that can reduce the amount of virgin material, maintaining the functionality of the product and reducing its total impact (Delogu et al., 2016; Luz et al., 2010).

The European strategy for plastics outlines the challenges and commitments for adopting transition measures toward a sustainable economy in the plastics sector, in which 29.1 million tons were managed in 2018 (PlasticsEurope, 2020). This recycling management has been decelerating, stagnating at a plastic packaging recycling ratio of 66% in 2018 (European Environment Agency Waste Recycling, 2022), and with alarming numbers of plastics that still end up in landfills (25% of plastic waste collected (PlasticsEurope, 2020)). To upgrade this situation, improvements have been developed in recycling methods (Quaghebeur et al., 2013; Geng et al., 2022) and new technologies for biological and enzymatic recycling (Pirillo et al., 2022; Yoshida et al., 2016; Viljakainen and Hug, 2021). Other promising solutions focus on the recovery of this waste to obtain highvalue products such as H_2 (Cortazar et al., 2022; Xuan et al., 2022), high-grade pyrolysis oil (Abnisa and Wan Daud, 2014), or catalysts and other chemical compounds of interest (Samorì et al., 2021). However, all these actions do not reduce thermoplastic consumption, so replacing conventional thermoplastics derived from petroleum with natural materials can be a more sustainable alternative.

Advances in the development of biomaterials and biopolymers allow the progressive substitution of petrochemical plastics, as they are renewable, environmentally friendly, and biodegradable materials (Sadasivuni et al., 2020; Mohanty et al., 2000, 2005). It is the case of starch, extracted from many natural sources (Guo et al., 2021) and used from foams and films (Hassan et al., 2019; Kumar et al., 2019; Guo et al., 2021) for energy storage (Hemamalini and Giri Dev, 2018). On the other hand, polylactic acid has become one of the most widespread and studied biopolymers due to the ease of obtaining it, the variety of sources (Lim et al., 2008; Farah et al., 2016; Jem and Tan, 2020), and its wide application versatility (Balla et al., 2021), such as 3D printing (Tümer and Erbil, 2021), medical applications (Ebrahimi and Ramezani Dana, 2021; DeStefano et al., 2020; Tyler et al., 2016), the automotive industry (Bouzouita et al., 2018; Adesina et al., 2019), textile (Yang et al., 2021), or electronic components (Mattana et al., 2015), among many others. However, cellulose is the most abundant, low cost and oldest biopolymer known (Moon et al., 2011a, 2011b), which continues to be the subject of continuous developments and applications in practically any field (Liu et al., 2021; Joseph et al., 2020; Klemm et al., 2011; Sharma et al., 2019). Thus, cellulose fibers extracted from innumerable plant species such as flax, hemp, jute, ramie, or sisal, have shown their enormous potential as reinforcement due to their lightness, abundance, and specific properties like those of fiberglass (AkashSreenivasa Rao et al., 2016; Bledzki et al., 1996), improving properties in all types of thermoplastics and applications (Kusić et al., 2020a; Aranberri-Askargorta et al., 2003; Mihalic et al., 2019; Qin and Fancey, 2018; Ferreira et al., 2019; Chee et al., 2020).

Among the existing cellulose fibers, Canary banana pseudostem fiber (Dwarf Cavendish) has better specific mechanical properties (in relative terms referred to fiber weight) than other commercial natural fibers such as sisal, jute, or flax, with average values of tensile strength of 891 MPa and elastic modulus of 42.8 GPa (Benítez et al., 2013), and corresponding values of specific tensile strength of 660 MPa cm^3/g and specific elastic modulus of 31.7 GPa cm^3/g (considering 1.35 g/cm^3 density). This has allowed the development of cost-effective and high-value compounds with a better life cycle (Gupta and Tiwari, 2020), which can be focused on countless applications, competing with other natural and synthetic fibers such as fiberglass (Joseph et al., 2002). Different applications with banana fiber (BF) have been investigated, for example, in ABS, HDPE, PP, or HIPS compound reinforcements with different percentages of fiber through injection molding processes (Kusić et al., 2020b; Ortega et al., 2010), in rotational molding processes (Monzón et al., 2012; Ortega et al., 2013), in the manufacture of fabrics made from BF yarn and wool (Ortega et al., 2016), in flame retardant applications (Nguyen and Nguyen, 2021; Ortega et al., 2020), or as reinforcement in biodegradable bags from biobased materials (Bordón et al., 2021).

These applications can stimulate the economy, especially in regions such as the Canary Islands (outermost region of the European Union), where banana cultivation is the most widespread, generating more than 400,000 t lignocellulosic residues annually (Tarrés et al., 2017). Despite its potential, this vast amount of pseudostem residue is currently not being valued, being a potential source of natural, sustainable, and high-value resources that would allow the diversification of the economy in the Canary Islands and the promotion of a circular economy in line with the global climate change and energy transition objectives of the Canary Islands.

On the other hand, Life Cycle Assessment (LCA), standardized by ISO 14040:2006 (International Organization for Standardization, 2006a) and 14044:2006 (International Organization for Standardization, 2006b), allows for determining the environmental aspects and potential impacts during the life cycle of a product, such as the carbon footprint, which allows calculating the contribution of a product to global warming in terms of CO_2 equivalent (Zhao et al., 2022); but also under other environmental methodologies, that provide a broader impact assessment (Carvalho et al., 2019; Lamnatou et al., 2018). This methodology allows the evaluation of products (Degen and Schütte, 2022; Martínez et al., 2009; Elduque et al., 2014), processes (Gaudreault et al., 2009; Filleti et al., 2017), or services (Neramballi et al., 2020; Bartolozzi et al., 2018). Regarding product development, it allows quantifying eco-design alternatives, evaluating not only the impact produced during the different stages in the life of a product but also its possible reduction by incorporating greater quantities of recycled material (Dormer et al., 2013), the influence of the type of package designed (Wu et al., 2013), the type of material used (Górny et al., 2021), the effects of transport and logistics (Rosmiati, 2020; Rodríguez et al., 2020a) or the reuse and recycle options (European Environment Agency Waste Recycling, 2022; Rodríguez et al., 2020b).

Recent studies have parameterized life cycle inventory data for other banana species, confirming the low impacts associated with fiber extraction and production (Elduque et al., 2015; Prasad et al., 2016). It has also been determined how replacing higher impact biopolymers (PLA) with BF allows a global improvement of the impact on injected compounds (Prasad et al., 2016). On the other hand, other studies have analyzed the different variables that can affect the environmental impact on injection molding processes, and the variability of results that can be obtained based on the Life Cycle Inventory values data used (Elduque et al., 2015). All these investigations confirm the suitability of BF as a biomaterial for compounds with a lower environmental impact. However, they do not assess the mechanical improvements introduced by the fiber or the repercussions that this entails in the redesign and optimization of final products.

This work analyzes, using LCA, the effects produced by the treatments and processing of the fiber in the development of HDPE compounds reinforced with different concentrations of short BF, to obtain compounds with higher mechanical performance and less impact on their life cycle. Unlike other studies, thickness optimizations (taking advantage of the reinforcement effect generated by adding BF) have been carried out in a case study made with these compounds. Therefore, for each compound, the thickness was reduced until matching the original mechanical characteristics of the studied component (pure HDPE) in terms of stiffness and thus, reducing the amount of

thermoplastic needed. LCA studies have been carried out to evaluate the impacts produced not only by incorporating fiber in these compounds but also by the possible optimization of the material, improving its environmental impacts.

2. Materials and methods

2.1. Banana fiber extraction and mechanical processing

BF extraction has been carried out using the pilot plant developed by the University of Las Palmas de Gran Canaria, with a patented BF extraction machine (patent number WO 2014/174115 A1), which allows the separation of BFs from the leaves of the pseudostems. The pilot plant scraps the banana leaf, extracting its pulp but keeping the fiber in a long format. It consists of three differentiated electromechanical systems to develop the extraction process (Fig. 1).

The clamping and transport of the banana leaves through the scraping systems is carried out through a linear system with continuous clamping by an electric gear motor. The pseudostem leaves, previously cut and laminated manually, are introduced into the feeding area of the machine, placing them into the jaws area to produce their grip and subsequent movement along the machine. The operation of this system is continuous, going through the two scraping modules of the device to end in the discharge area of the separated fiber. Even though the number of leaves being simultaneously transported is variable, the energy consumption of the transport system components is relatively constant according to the experimental measurements.

The first linear scraping system (module 1) produces a first separation of the outer layers of the banana leaf and pulp through a set of horizontally arranged blades. These blades move vertically, tangentially shearing the pseudostem leaves, from the upper clamping part to the lower part of the blades and on both sides. The scraping process takes place in a few seconds while the gripping and transport system continues its movement. A second electric gear motor propels the scraping drive system. During the scraping process under load conditions (leaf being scrapped), the electrical consumption increases by around 30% compared to the no-load operation (without leaf). For this reason, the consumption and effective scraping times with the passage of banana leaves have been monitored to determine the real consumption of a fiber extraction cycle.

A second rotational scraping system (module 2) is carried out by transporting and guiding the leaves to a horizontal rotating drum at high speed, where a set of peripheral metal blades scrapes the banana leaves against a static rear support surface. This second process produces a final pulp extraction. The regulation of the distance between the rear support surface and the drum blades makes it possible to control the cleanliness level of the fiber obtained. Similarly to module 1, the energy consumption of this second scraping is generated by a third electric motor in which the under-load operation increases the consumption by 81% (on average). Therefore, monitoring the consumption and times with and without load during a standard fiber extraction cycle was also necessary.

In order to obtain short fiber with homogeneous size, a subsequent cutting and screening process has been developed. After natural drying, the extracted fiber was cut to a 2 mm length using a rotational cutting machine designed and manufactured for this purpose. This machine includes the transport of the long fiber dried through an electromechanical belt system, cutting the fiber by rotating blades, and automatic storage by aspiration. Finally, a rotating mesh drum allows the fiber to be sieved, obtaining a homogeneous distribution of the fiber, and separating the long fibers that were not cut. All these processes are driven by electric motors that work continuously with constant electricity consumption.

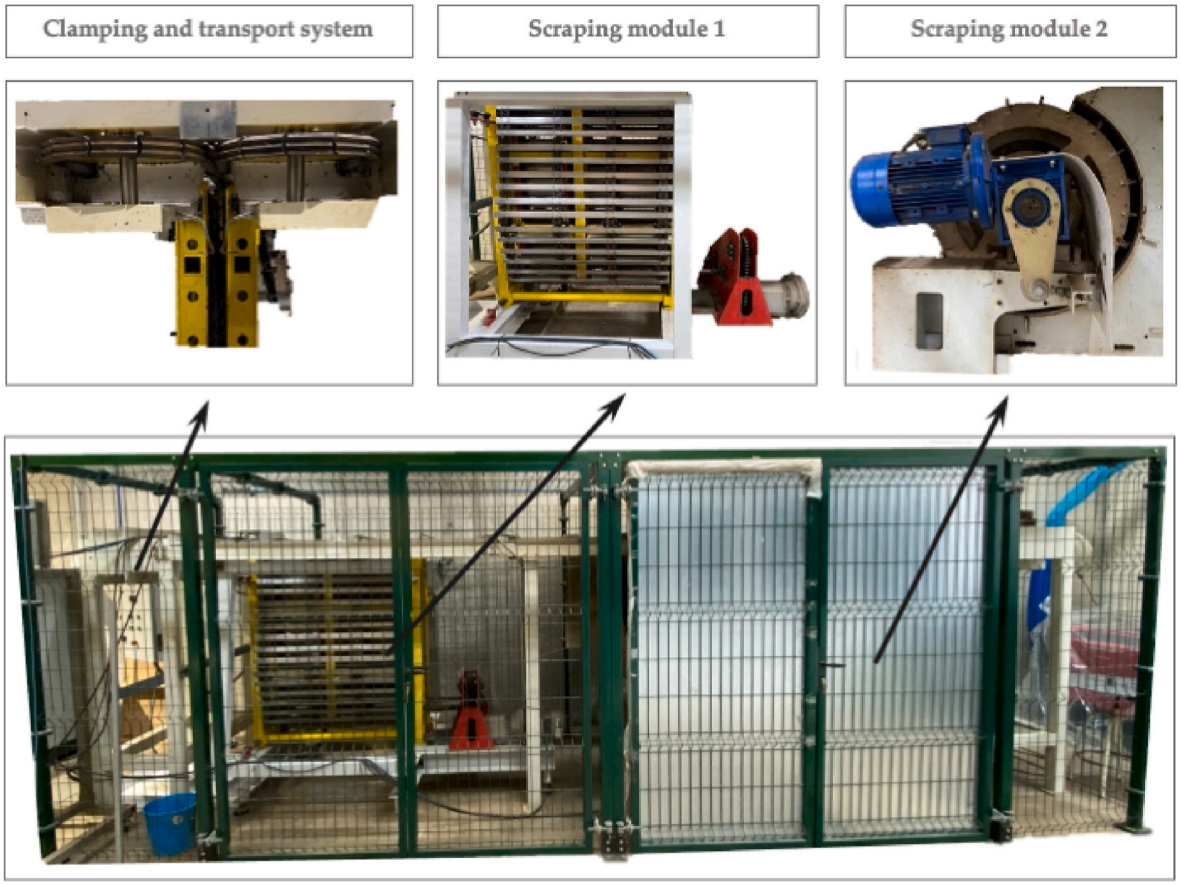

Fig. 1. Main electromechanical components of the patented machine for extracting fiber from banana pseudostem.

Previous work has shown that combing the fiber before the cutting process could replace the fiber's chemical treatment, improving its processing's sustainability and cost (Bordón et al., 2021). Therefore, this modification of the fiber processing has been included and analyzed in this work. For this, in the scraping module 2, 5 brushes of 25 mm length were assembled in the final part of the blades.

2.2. Banana fiber treatment

The fiber treatment is a common post-processing used to improve both fiber matrix integration and degradation temperature, mainly by an alkali treatment (Ortega et al., 2013; Dassault Syst è mes Simulia Corp; The MathWorks and Inc, 2021). Chemical treatment was carried out by a bubble column reactor with a solution of NaOH 1N, in batches of 200 L and a maximum amount of 5 kg of chopped fiber for 1 h at room temperature. Recirculation and agitation systems were used to optimize the process. Finally, the fiber treated was centrifuged and dried in a continuous rotational drier with infrared lamps.

2.3. Banana fiber generations

Three types of BF have been differentiated according to the mechanical and chemical treatment processing applied (Fig. 2). A first generation was obtained by extraction processing (including fiber chopping to 2 mm length), chemical treatment, and non-natural drying. A second generation of fiber was improved by including fiber sieving, necessary to obtain fibers with homogeneous lengths before the chemical treatment. Although previous works have confirmed the mechanical properties of this treated fiber (52 GPa of tensile modulus and 687 MPa of tensile strength (Benítez et al., 2013)) and its reinforcement properties in polymeric compounding (Kusić et al., 2020a), in some cases, the improvements that this treatment produces could not be necessary, or the additional cost or impact could not be justified from an economic or environmental point of view. For this reason, a third fiber generation was developed by extracting fiber with a final combing process and a subsequent natural drying, cutting, and sieving (the combing process replaced the chemical treatment and, consequently, avoided the non-natural drying).

Environmental impact analysis has been carried out for the 2nd and 3rd generation of fiber since the 1st generation has been considered as a preliminary fiber used to improve the rest of the fiber generations. On the other hand, the main interest of this work is to compare the 2nd and the 3rd generations, where the chemical treatment is the main difference and could make a difference in terms of sustainability.

Since HDPE compounds reinforced with treated fiber (2nd generation of fiber) were already characterized in previous studies (Kusić et al., 2020a), in this work, only 3rd generation fiber-reinforced compounds were performed for mechanical and thermal characterization.

2.4. Polymeric matrix and banana fiber content

The polymeric matrix used was HDPE from Egyptene HD 6070UA since this was the original material of the case study component (mounting sleeve).

The polymer matrix and three different percentages of 3rd generation BF were used (10, 15, and 20 wt %) according to the desired effect on the final functional components to be manufactured with this compound material.

2.5. Compounding and injection molding processes

LABTECH – LTE 20–40 twin screw extruder was used to manufacture the three percentages of HDPE and BF compounds. The extrusion process was carried out at a temperature distribution between 142 and 161 °C, a screw rotation speed of 400 rpm, a feed speed of 18.2 m/min, and a 23-bar pressure. Afterward, the extruded compound was chopped at 4 mm length.

The test samples and case study components were injected in an Engel e-Max 440/100 machine with all the material combinations (pure HDPE and 10, 15, and 20 wt % BF content). The compounding was injected at a maximum pressure of 487 bar and a temperature on cylinder heating zones between 170 and 185 °C. The case study components were injected with an injection speed of 200 mm/s, 500 kN of clamping force, and a packing pressure of 100 bar for 4 s.

2.6. Mechanical test

Tensile tests (5 samples of each compounding) were performed in accordance with ISO 527 to determine the elastic modulus, tensile strength, and elongation at break. The samples were tested with a jaw spacing of 50 mm, 1 mm/min of initial load speed, and a secondary speed of 50 mm/min until the break.

Three-point flexural tests were also carried out with other 5 samples for each compounding following ISO 178. The distance between supports was 64 mm, and the displacement speed was 2 mm/min.

Both tensile and bending tests were carried out in a Shimadzu AG - X plus 10 kN testing machine.

Additionally, impact strength and notch impact strength tests were made with a Charpy LY-XJJDS device, according to ISO 179, and using 2

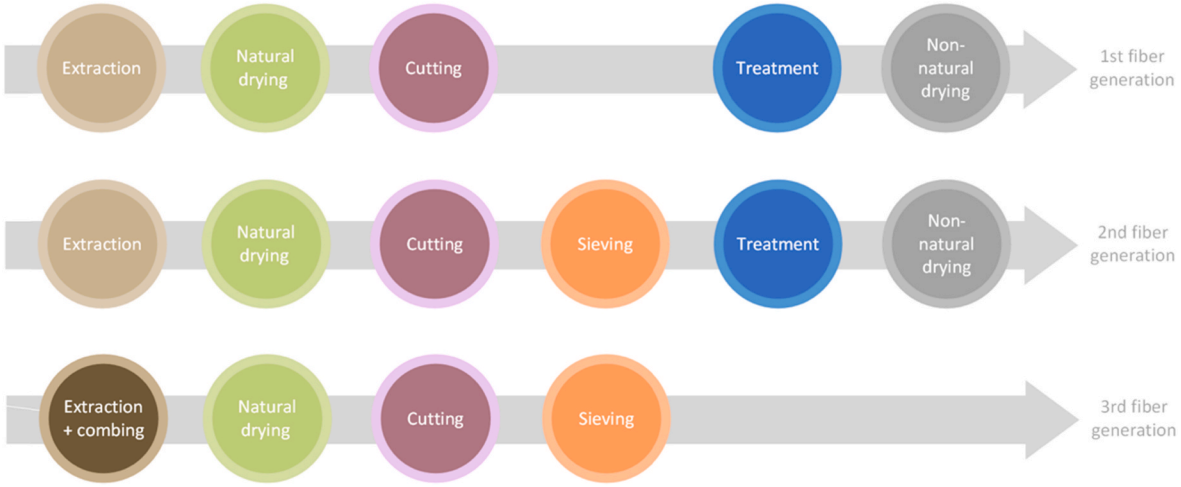

Fig. 2. Fiber generation and processing schema.

mm thickness and 5 mm width samples. The tests were carried out with a 2 J hammer and a 60 mm distance between supports.

2.7. Thermal gravimetric analysis (TGA)

To determine the thermal characteristics of the compounds, TGA analysis (and derivative thermography DTG) was carried out using a PerkinElmer TGA 4000.

A nitrogen atmosphere was used to degrade organic components, and an oxygen atmosphere to obtain oxidizing conditions and burn the carbonaceous material, leaving behind inorganic components.

The thermal cycle in the nitrogen atmosphere was carried out for 1 min at 40 °C, and a final heating at a rate of 10 °C/min up to 550 °C. The oxidative cycle was performed at the same temperature (550 °C) for 10 additional minutes.

2.8. Development and simulation of a real case study

The test case used for this study was a mounting sleeve for air-conditioned units. The original mounting sleeve is made of pure HDPE, with a 115 mm internal diameter, a 31.6 mm length, and a 3.5 mm thickness. Since the compounding materials have higher mechanical properties than pure HDPE due to the fiber content, these materials may lead to stiffer mounting sleeves, hindering the assembly process. To evaluate this effect, mounting sleeves with the different materials (pure HDPE and reinforced compounding) were produced and tested by applying a compression radial force (centered in the length of the perimeter) until the inner face of the ring touched a reference shaft of 106 mm diameter, which implies a 9 mm deflection of the internal face, as depicted in Fig. 3.

On the other hand, the mounting sleeves were modeled and simulated by Finite Element Analysis (FEA) in Abaqus software (Dassault Syst è mes Simulia Corp) to determine, for each compound material, the thickness required to achieve the same stiffness as the original HDPE mounting sleeve (the stiffer the material, the lower the thickness needed). To do so, 1/4 of the mounting sleeve was modeled, taking advantage of the double symmetry of the geometry and boundary conditions (Fig. 4).

Therefore, the faces of the symmetry planes were constrained in the normal direction (Z restriction for the face in the XY plane and X restriction for the face in the ZY plane). A base and a crosshead were also included in the simulation as rigid solids. The base was encastred while the crosshead was also constrained in the normal direction of the symmetry planes (Z restriction for the face in the XY plane, and X restriction for the face in the ZY plane), and a downward vertical displacement of 9 mm was applied. A surface-to-surface interaction was defined between the mounting sleeve and the base and crosshead, with frictionless tangential and hard-contact normal behaviors. The models were meshed with a linear structured hexahedral mesh (linear brick element with 1 integration point, C3D8R) and 1 mm seed size. Non-linear effects of large deformations and displacements were considered as, in this case, the mounting sleeves lose stiffness during the compression due to the geometry deformation.

A post-processing step was included to determine the vertical reaction force in the crosshead. Due to double symmetry, the simulated reaction force was multiplied by 4 to obtain the real reaction force. With this model and methodology, the produced rings were simulated using the original shape of the mounting sleeves (3.5 mm thickness). The Poisson's ratio was 0.4101, and the elastic modulus for each material is shown in Fig. 7. The simulated reaction force was compared with the experimental one, and a correction factor was determined for each material (real force divided by simulated force). This correction factor was later considered to correct the force of the simulations (simulated force multiplied by the correction factor), thus obtaining more realistic values.

Finally, for each compounding material, the thickness of the mounting sleeve was iteratively adjusted by carrying out several simulations until achieving the same reaction force as in the original HDPE mounting sleeve (Fig. 5). For this to happen, firstly, a new thickness was applied, and the model was regenerated and simulated accordingly. The obtained reaction force was multiplied by 4 (to consider the double symmetry) and updated with the correction factor. Then, the available data (corrected reaction force and corresponding thickness) were used to estimate, with a cubic spline data interpolation function in MATLAB (The MathWorks and Inc, 2021), the thickness needed to achieve the same reaction force as the original mounting sleeve (pure HDPE with 3.5 mm thickness). The estimated thickness is then updated in the FEA model, and the simulation is repeated. If the corrected reaction force is similar to the one of the original mounting sleeve (error lower than 0.2%), then the thickness is already adjusted, and the volume of the mounting sleeve is determined (volume of the model multiplied by 4). Otherwise, the required thickness is estimated again with the cubic spline interpolation but including the last data (this process is repeated in a loop until the thickness is correctly adjusted, which means an error lower than 0.2%).

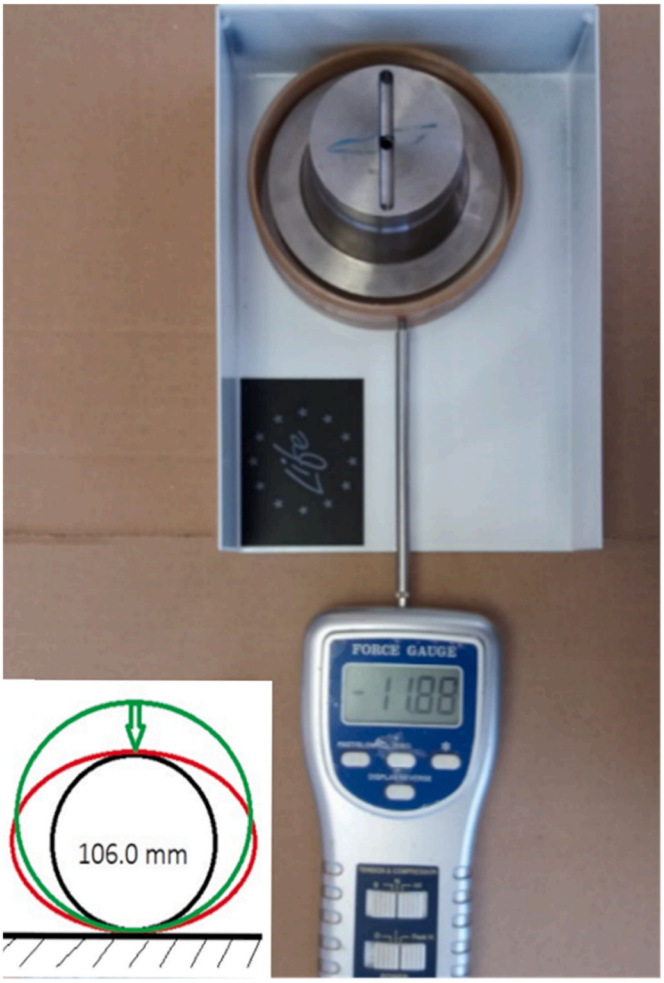

Fig. 3. Schematic configuration of the compression tests carried out in the mounting sleeves.

2.9. LCA methodology

LCA has been carried out following ISO standards 14040 and 14044 (International Organization for Standardization, 2006a; International Organization for Standardization, 2006b) to assess the environmental impact of the polymer compounds under different project scenarios and compare them with the original scenario in which pure HDPE is used.

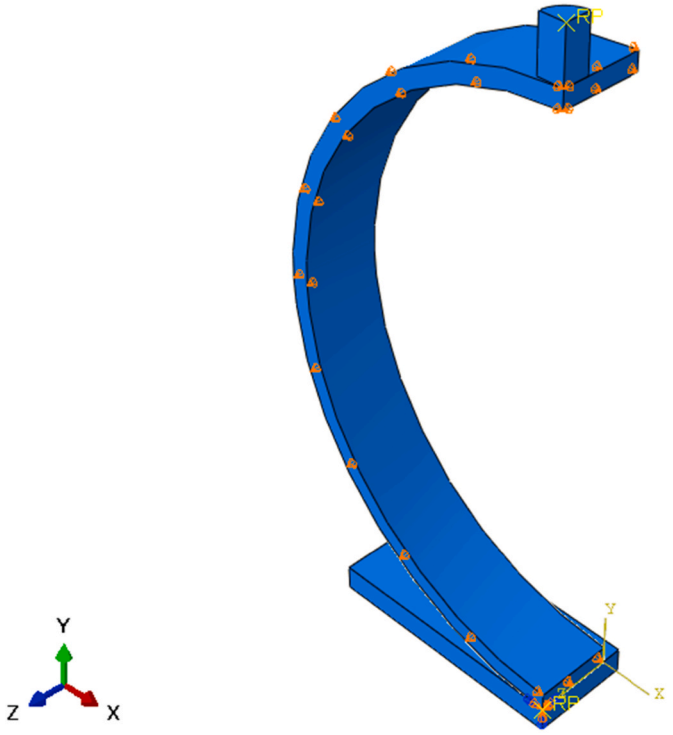

Fig. 4. FEA model for the simulation of the mounting sleeves.

This Life Cycle Inventory (LCI) compares these scenarios with a "cradle to grave" scope, including raw materials acquisition, manufacturing, transportation, and end of life. A conservative approach has been considered regarding the End of Life phase since the plastic components (air-conditioned mounting sleeves) will be sent to a landfill after its use phase. This is also considered adequate as polymers with biobased fillers are not usually separated and recycled. The LCI is based on primary data and uses the EcoInvent v3.2 database, one of the most relevant LCI databases (Wernet et al., 2016), and SimaPro v8.2 as the calculation software (Pre Consultants SimaPro 8 Database, 2013).

The environmental impact on the different scenarios was calculated using two methodologies, ReCiPe 2013 Endpoint (H/A) and the IPCC 2013 GWP 100 years (Pre Consultants SimaPro 8 Database, 2013). ReCiPe provides a global result, enhancing the interpretation of the results and considering a broad range of environmental impacts (Dong and Ng, 2014). The IPCC 2013 GWP Carbon Footprint methodology focuses on greenhouse gas emissions and has also been selected due to its social relevance (Dryzek et al., 2011).

The original component of the case study was manufactured with pure HDPE. The functional unit selected for this paper has three different formats that will be used to compare the results, both for second and third-generation fibers, with the previous situation:

1) The environmental impact of a kg of the compound prepared to be injected with HDPE and 10, 15, 20, 25, and 30 wt % of BF.
2) The environmental impact of an injected plastic component (mounting sleeve for air-conditioned units) manufactured with the materials mentioned above.
3) The environmental impact of a mounting sleeve functionally optimized according to the fiber percentage used (the thickness is adjusted based on mechanical properties, as previously explained).

2.10. Life cycle inventory, LCI

Following the Life Cycle Assessment framework, an LCI is carried out to evaluate the environmental impact of both fiber generations.

The quantity considered in these calculations is 125 kg of leaves of the pseudostem of banana tree for each kg of fiber obtained that is needed.

Next, the elements considered in each process are shown, which affect the environmental impact they generate. Also, several tables are provided with the parameters used for the calculation.

It is worth mentioning that the banana pseudostem is currently an agricultural residue left in the field to degrade naturally. In this work, the banana pseudostem is transformed into useful BFs. However, to provide a more conservative approach regarding the environmental impact calculations, it has not been considered that this waste reduction reduces the amount of emissions created by this waste. Therefore, no environmental credit was applied due to the reduced agricultural residue left to degrade.

2.10.1. Fiber extraction

The extraction process is the same for both fiber generations except for the combing process included in the third generation.

To calculate its environmental impact, the energy consumption, machinery (1350 kg) and the infrastructure occupation (13.5 m^2), have been considered. The extraction process comprises several subprocesses, which have been measured individually: clamping-transportation and scraping. The combing process did not produce an increase in energy consumption.

To obtain the adequate consumption of fiber extraction, a complete extraction cycle was carried out where all the electrical consumption and operating times of all the extraction machine systems were monitored, both in the periods with and without load. Table 1 summarizes the main parameters of the fiber processing during a regular cycle of extraction. Note that the production and specific consumption are calculated in terms of the mass of dried fiber (D.F.).

2.10.2. Fiber cutting

The cutting process is also the same for both fiber generations. Energy consumption, machinery (300 kg), and infrastructure occupation (3 m^2) are also considered.

The environmental impact of the fiber extraction process is calculated as the addition of the environmental impact produced by the machinery paid off throughout all its production, plus the share associated with the plant occupation and the infrastructure use, plus the impact corresponding to the energy consumed in the process. Some of the fibers (around 7%) are discarded in the process, and their waste is also considered. Table 2 summarizes the main parameters of the fiber processing during an average cycle of cutting and sieving.

Extraction, cutting, and sieving are all the required processes for the

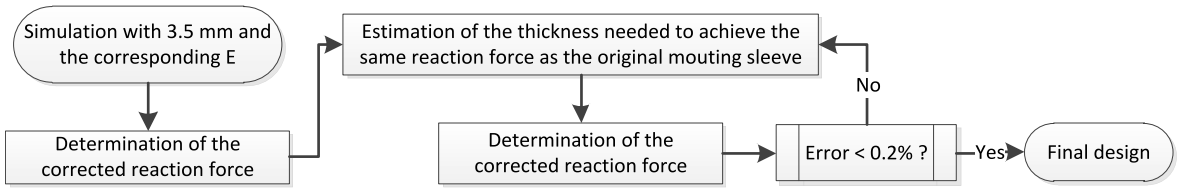

Fig. 5. Workflow for adjusting the thickness of the mounting sleeves for each compounding material to maintain the stiffness of the original HDPE mounting sleeve.

Table 1
Main parameters of fiber extraction.

System	Power (kW)	Current on load (A)	Energy consumption (Wh)	Production (kg D.F./h)	Specific consumption (Wh/kg D.F.)
Clamping and transport	3.00	3.97	3749.58	43.0	87.20
Scraping module 1	3.00	1.41	1222.88	43.0	28.44
Scraping module 2	3.00	4.35	4882.30	43.0	113.54
Total Extraction					**229.18**

Table 2
Main parameters of fiber cutting and sieving.

System	Power (kW)	Current on load (A)	Energy consumption (Wh)	Production (kg D.F./h)	Specific consumption (Wh/kg D.F.)
Cutting belt	0.37	0.40	205.07	3.60	56.96
Cutting rotation	1.10	1.50	820.99	3.60	228.05
Aspiration	0.75	1.35	750.00	3.60	208.33
Sieving	0.25	0.45	250.00	6.00	41.67
Total cutting and sieving					**535,01**

third-generation fiber. However, the second generation required additional processes (chemical treatment and drying), which were also considered, as explained in the following section.

2.10.3. Treatment and drying

These processes are only needed for the second-generation fiber. Two recirculating pumps and air agitation, with 550 Wh and 2050 Wh of total electric consumption, respectively, allow the treatment process. The efficiency of the reactor in terms of weight loss of fiber is about 80%. Therefore, from 1 kg of raw fiber, 0.8 kg of treated fiber is obtained. Additionally, the alkaline solution can be used several times. The real tests show that this treatment requires 1.05 L of NaOH solution (1N), 151 L of water, 0.33 m^3 of compressed air, and 4745.0 Wh of electrical energy for each kg of dried fiber.

The wet-treated fiber was centrifuged at 1000 rpm in a continuous rotational drier with a constant energy consumption of 256,97 Wh. Several infrared lamps dried the fiber completely using 4255.17 Wh. The drying process allowed obtaining 0.56 kg of dried fiber per hour with an energy consumption of 8057.4 Wh per kg of dry fiber. After drying, the fiber was ready for the following step of compounding extrusion with the thermoplastic matrix. Table 3 shows the consumption of fiber treatment and drying.

2.10.4. Compounding and component injection

To calculate the impact of the compound obtained, the impact of the fibers (second and third generation) plus the HDPE matrix were considered. In the case of the fibers, the transportation from the production plant to the compound generation plant was included, which adds 2300 km of freight ship, plus 10 km from the port to the compound factory. The generation process of the compound by plastic extrusion was also considered.

Once the compound is obtained, it can then be injected. EcoInvent injection molding dataset has been used to consider this process. For the injected components, the environmental impact of their end of life (landfilling, as previously explained) was also considered.

3. Results and discussion

3.1. Thermal characterization (3rd generation fiber)

TGA results (Table 4) show the technical behavior of the HDPE matrix and compounds with the different percentages of BF. The degradation temperature (peak T_2) of HDPE was practically unchanged by the fiber addition, with variations of less than 0.54%. Even 20 wt % BF compound showed almost the same temperature degradation as pure HDPE. Fiber degradation was clearly observed in the first degradation peaks (T_1) at temperatures close to 350 °C. The incorporation of higher percentages of fiber decreased the peak degradation temperature T1, progressively approaching the values of untreated fiber degradation temperature, around 330 °C (Benítez et al., 2013). Therefore, it is ruled out that the integration of fibers in the HDPE matrix affects the degradation temperature for the application developed in this work, where the injection molding process does not exceed the forming temperatures of 185 °C.

Concerning the loss of mass, as expected, the incorporation of higher percentages of fiber produced more significant losses of degraded mass and the generation of greater amounts of ash incorporated into the compound by the BF.

Regarding the Differential Scanning Calorimetry (DSC) analysis shown in Table 5, the compound material melting temperature is essentially the same as for pure HDPE, which for the injection molding process, does not imply changes in the main thermal parameters when incorporating the BF.

The first cycle of DSC shows how the specific enthalpies of fusion and crystallization decreased with increasing BF content. The addition of fibers produced compounds that required less melting energy (−21.45% compared to pure HDPE) and compounds with less crystallinity due to the heterogeneous distribution of the fiber and its orientation within the compound, which restricts molecular growth. These effects are similar to those found in other HDPE compounds reinforced with natural fibers (Benítez et al., 2013; Wernet et al., 2016). As for the crystallization enthalpy, it was reduced to 19.2% in the compounds with higher

Table 4
TGA of BF compounds.

Sample	Weight loss [a] (%)	Peak T_1 (°C)	Peak T_2 (°C)	Ashes (%)
Pure HDPE	–	–	490.20	0.358
HDPE + 10 wt % BF	7.21	351.72	489.78	0.622
HDPE +15 wt % BF	9.11	347.19	487.57	0.605
HDPE +20 wt % BF	12.00	345.47	490.76	1.072

[a] BF decomposition.

Table 3
Main parameters of fiber treatment and drying.

System	Water consumption (l/kg D.F.)	NaOH consumption (l/kg D.F.)	Specific consumption (Wh/kg D.F.)	Production (kg D.F./h)	Machine weight (kg)	Occupied surface (m^2)
Treatment	151	1.05	4745.0	0.56	50	9 m^2
Drying	–	–	8057.4	0.56	400	1.8 m^2

Table 5
First and second cycles DSC of BF compounds.

Sample	First DSC cycle				Second DSC cycle			
	T_m (°C)	ΔH_m (J/g)	T_c (°C)	ΔH_c (J/g)	T_m (°C)	ΔH_m (J/g)	T_c (°C)	ΔH_c (J/g)
Pure HDPE	134.1	183.5	116.7	205.0	133.2	207.6	117.9	209.1
HDPE + 10 wt % BF	134.1	154.6	116.9	179.3	133.5	180.4	117.8	180.9
HDPE +15 wt % BF	134.1	145.9	118.3	171.1	133.3	172.8	118.4	171.7
HDPE +20 wt % BF	134.3	144.1	117.8	165.7	133.4	167.1	118.3	165.9

percentages of BF.

Similar results were obtained in the second cycle of DSC, where no relevant changes in melting and crystallization temperatures were found. Furthermore, similar enthalpy reductions were achieved, around −19.5% and −20.7%, respectively.

3.2. Mechanical properties (3rd generation fiber)

In general, and as expected, the incorporation of fiber increased the stiffness in the compound (the higher the fiber content, the higher the tensile modulus, as shown in Fig. 6 for the tensile tests). Specifically, 10 wt % BF compounds increased the tensile modulus by around 44% compared to pure HDPE. An additional increase of tensile modulus was observed from 10 to 20 wt % BF, but, in this case, the increase was lower (31.3%). Therefore, the increase in stiffness was not linear with the BF content and, for high BF contents, the reinforcement effect was lost. No significant changes were found regarding the maximum tensile stress since slight decreases were produced (up to 5 for 15 wt % BF).

Flexural tests showed similar mechanical behavior in elastic modulus, which also increased with the fiber content (Fig. 7). Concerning the maximum flexural stress and unlike the tensile test, higher BF contents produced an increment up to 25% (when comparing 20 wt % BF to the pure HDPE).

The increased stiffness of the fiber incorporation reduced the impact strength of the compounds, as shown in Fig. 8 (impact tests). In the case of 20 wt % BF, the impact strength was reduced by more than half compared to pure HDPE.

These mechanical results show a similar behavior without significant differences between the second-generation fiber (chemical treatment) (Kusić et al., 2020a) and the third-generation fiber (combed and without chemical treatment). Thus, the incorporation of untreated but combed fiber also makes it possible to obtain reinforced HDPE compounds with improved mechanical performance in traction and bending despite the lower fiber-matrix integration due to the absence of chemical treatment of the fiber (Ortega et al., 2013; Dassault Syst è mes Simulia Corp).

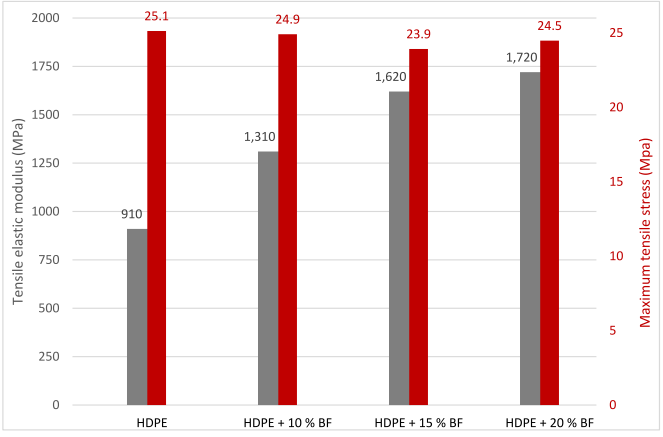

Fig. 6. Tensile elastic modulus and maximum tensile stress of HDPE compounds.

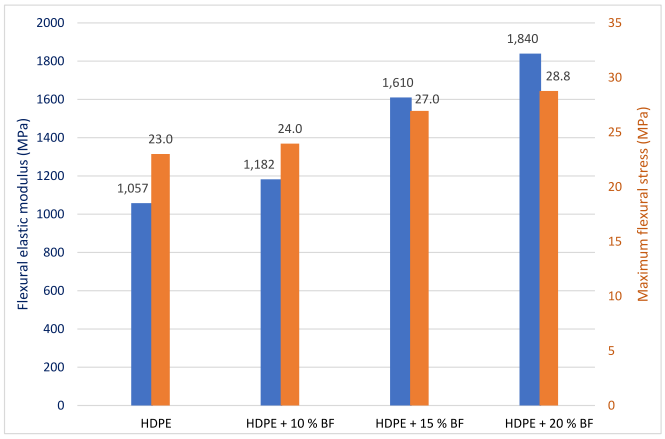

Fig. 7. Flexural elastic modulus and maximum flexural stress of HDPE compounds.

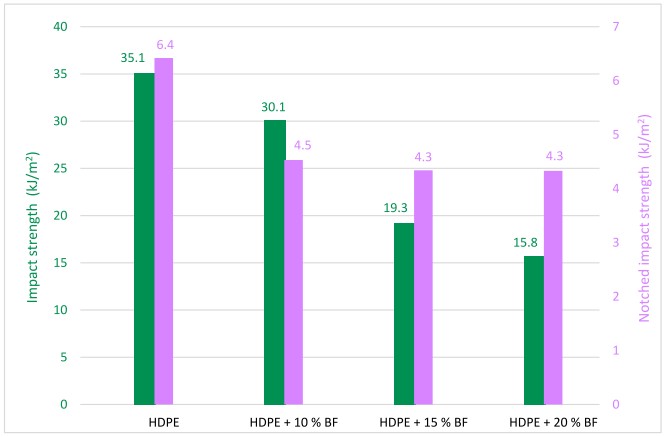

Fig. 8. Impact strength of compounds (notched and unnotched).

3.3. Case study tests (3rd generation fiber)

Fig. 9 shows the Von Mises stress obtained from the simulations of the mounting sleeves with the different materials (initial shape and deformed geometry after the 9 mm displacement of the crosshead). As expected, the higher the material elastic modulus, the higher the Von Mises stress generated during the deformation (from 8.179 MPa for pure HDPE up to 14.22 MPa for HDPE + 20 wt % BF, which means a 74% increase).

Table 6 shows the results obtained for the simulations of the mounting sleeves with the different materials. The second column (simulated force using the elastic modulus of the flexural tests, Fig. 7) represents the reaction force obtained in the simulations multiplied by 4 due to the double symmetry conditions applied in the model. The third column shows the forces obtained in the experimental tests of the mounting sleeves (Fig. 3) and for each material, being 31.42 N for the original mounting sleeve (pure HDPE). The error between the obtained

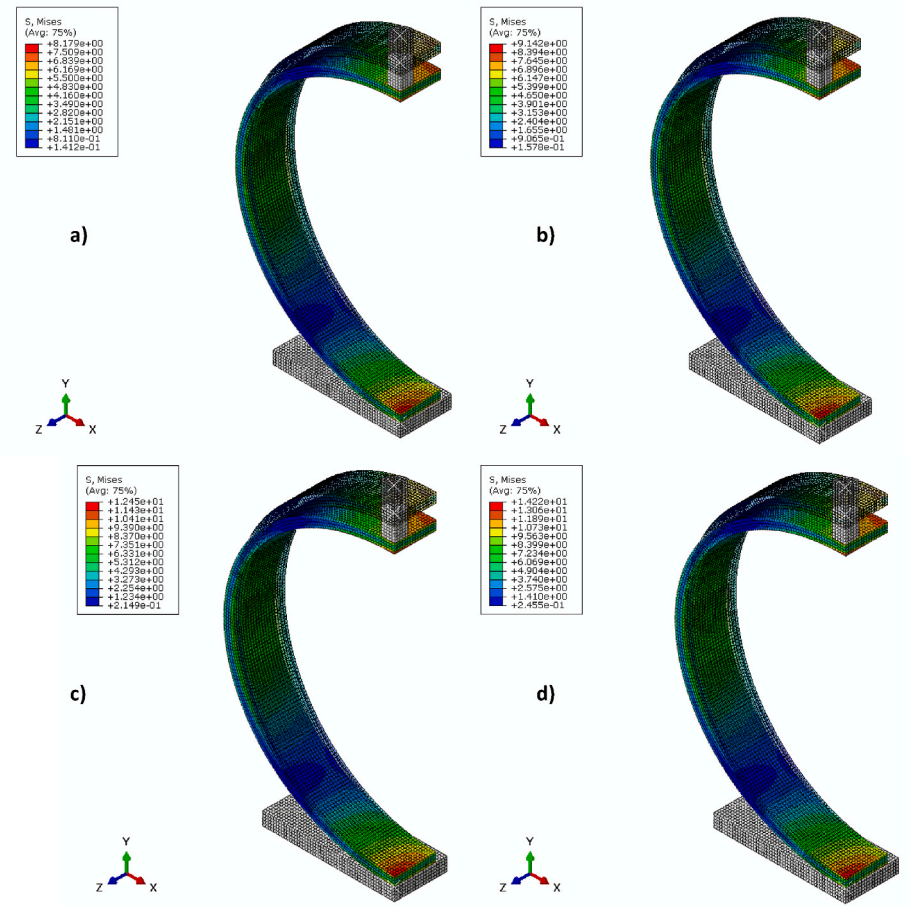

Fig. 9. Von Mises stress (in MPa) obtained in the simulations for the 3.5 mm thickness mounting sleeves with the different materials: (a) Pure HDPE; (b) HDPE + 10 wt % BF; (c) HDPE + 15 wt % BF, and (d) HDPE + 20 wt % BF.

Table 6
Results of the simulations and comparison with the obtained experimental forces.

Mounting sleeve material	Simulated force (N)	Real force (N)	Error (%)	Correction factor
Pure HDPE	31.14	31.42	−0.89	1.01
HDPE + 10 wt % BF	34.81	37.38	−6.88	1.07
HDPE +15 wt % BF	47.40	43.87	8.04	0.93
HDPE +20 wt % BF	54.15	48.58	11.47	0.90

experimental force and the simulated force was between −6.88 and 11.47% (fourth column). For the original HDPE mounting sleeve, the error between simulations and the real test was a mere −0.89%, significantly increasing with the fiber content. The last column depicts the correction factor for each material. These values were used to determine the corrected force to adjust the thickness of the mounting sleeves to match the experimental force of the original HDPE mounting sleeve (31.42 N).

Table 7 summarizes the results after adjusting the thickness of the mounting sleeves for each material. The second column depicts the density of the material, experimentally determined by weighting and measuring samples produced with the same process parameters. The mass of the optimized component (fifth column) was determined by multiplying the volume of the optimized mounting sleeve by the corresponding density. Finally, the HDPE and fiber mass (the last two columns) were determined through the fiber content (wt. %) of the related compound material.

Table 7
Results of the simulations and comparison with the real force of the experiments.

Mounting sleeve material	Density (g/cm^3)	Optimized thickness (mm)	Volume (cm^3)	Total mass (g)	HDPE mass (g)	BF mass (g)
Pure HDPE	0.847	3.500	41.174	34.860	34.860	0.000
HDPE + 10 wt % BF	0.889	3.354	39.408	35.049	31.544	3.505
HDPE +15 wt % BF	0.927	3.170	37.188	34.468	29.298	5.170
HDPE +20 wt % BF	0.935	3.061	35.876	33.547	26.838	6.709

According to the results, the use of 20 wt % BF in the compound material leads to a reduction of HDPE from 34.860 to 26.838 g (23.0%), both due to the replacement of HDPE by BF and the reinforcement effect of the BF (which allows a thickness and volume reduction of 12.5%).

On the other hand, some estimations were carried out for higher fiber contents (25 and 30 wt % BF). As these percentages were not developed and experimentally tested, these compounds' elastic modulus and density were estimated using the linear polynomial equation obtained by the least squares fitting. In the case of the elastic modulus, the data were corrected using the correction factor of Table 6. Fig. 10 shows the obtained equation for the elastic modulus, while Fig. 11 shows the corresponding to the density. In both cases, the coefficient of determination (R^2) was 0.97.

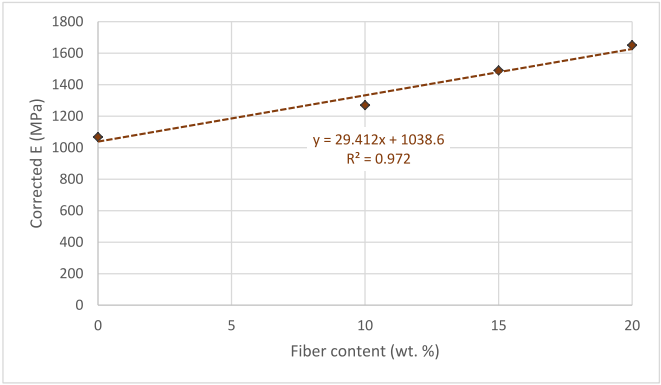

Fig. 10. Linear least square fitting of the corrected elastic modulus (E (MPa) = 29.412 · fiber content (%) + 1038.6).

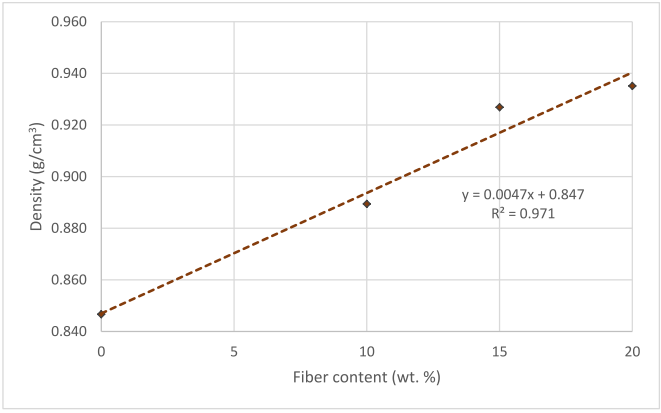

Fig. 11. Linear least square fitting of the density (density (g/cm^3) = 0.0047 · fiber content (%) + 0.847).

With the previous equations, the elastic modulus was determined and used for the FEA simulations and thickness optimization. The estimated density was also used to determine the final weight of the optimized ring. Table 8 shows the results.

The results show that higher BF contents allowed an additional reduction of the component thickness (and material of the matrix) for the same component stiffness. The higher simulated BF content (30 wt % BF) led to an optimized thickness of 2.9 mm (Table 8), implying a thickness reduction of around 17% compared with the original component. Consequently, the amount of HDPE was reduced by 32.6% compared to the original component, which could significantly affect the environmental impact analysis of the optimized components.

3.4. LCA results (2nd and 3rd generation fiber)

Different scenarios were calculated and compared with the original scenario (pure HDPE), analyzing an injected component with pure HDPE material and HDPE compounds with varying percentages of fiber obtained from the banana pseudostem through a second and third-generation process. The impacts of the material obtaining and the component mold injection process were assessed, considering 10 to 30 wt % of fiber content.

3.4.1. Original scenario (pure HDPE) versus new compound scenarios. Material obtaining

First, a comparison between the materials was carried out. After conducting all these cases, the following results (Table 9) were obtained, with the corresponding comparatives between the original scenario (pure HDPE) and the new scenarios considering the fiber (obtained from the banana pseudostem through the developed procedures) with the 2nd and 3rd generations and with the different fiber percentages.

The results show that most fiber compounds created higher environmental impacts than the original scenario (pure HDPE). Two main factors cause this. Firstly, obtaining the fiber is an energy-intensive process, especially for the second-generation fiber. Secondly, the compounded materials have additional processes due to the extrusion needed to generate the compound and the transportation of the fiber to the manufacturing plant.

Regarding fiber production, for the second generation, the environmental impact per kg of processed BF is 805.9 mPt and 8.20 kg eq. CO_2, which is higher than the corresponding impact values per kg of pure HDPE (268.6 mPt and 1.93 kg eq. CO_2, Table 9). Therefore, second-generation BF compounds create a higher environmental impact per kg than pure HDPE. On the other hand, as the third-generation BF has an optimized production process, its environmental impact per kg is much lower, 53.43 mPt and 0.50 kg eq. CO_2, which is lower than the impact values per kg of pure HDPE. Therefore, when the compound is created, although there are additional transportations and production processes, the environmental impact per kg of compound shows a decreasing tendency, obtaining lower values than for pure HDPE for fiber percentages over 15% in ReCiPe and over 25% in Carbon Footprint.

It also must be noted that pure HDPE creates environmental impacts per kg that are relatively lower than other thermoplastics. It means that substituting plastic with BFs would be much more beneficial for other

Table 9
Results of impacts for each compound kg.

BF generation	Material	ReCiPe (mPt)	Carbon Footprint (kg eq. CO_2)
–	Pure HDPE	268.6	1.93
Second	HDPE +10 wt % BF	359.7	2.90
	HDPE +15 wt % BF	387.4	3.22
	HDPE +20 wt % BF	415.2	3.55
	HDPE +25 wt % BF	442.9	3.87
	HDPE +30 wt % BF	470.7	4.19
Third	HDPE +10 wt % BF	284.4	2.13
	HDPE +15 wt % BF	274.6	2.07
	HDPE +20 wt % BF	264.7	2.01
	HDPE +25 wt % BF	254.8	1.94
	HDPE +30 wt % BF	244.9	1.88

Table 8
Estimations carried out for higher fiber contents (25 and 30 wt %).

Mounting sleeve material	Estimated corrected elastic modulus (MPa)	Estimated density (g/cm^3)	Optimized thickness (mm)	Volume (cm^3)	Total mass (g)	HDPE mass (g)	BF mass (g)
HDPE + 25 wt % BF	1773.90	0.965	2.987	34.987	33.745	25.309	8.436
HDPE +30 wt % BF	1920.96	0.988	2.903	33.974	33.566	23.496	10.070

polymers, such as polyamides, which have environmental impacts ranging from 750 to 850 mPt and 8–9.5 kg eq. CO_2.

3.4.2. Original scenario (pure HDPE) versus new compound scenarios. Injected components with the original thickness

Once the compounds were produced, they were injected to create the mounting sleeves. The original thickness (3.5 mm) and volume (41.174 cm^3) were considered in this subsection. This means that pure HDPE was replaced by a filled compound using the same injection mold without adjusting the thickness based on the mechanical properties. Table 10 shows the environmental impacts obtained.

Table 10 shows, as expected, that all the components injected with the second-generation fiber create higher environmental impacts than the one injected with pure HDPE. This is caused by the fact that the impacts per kg of second fiber compounds are higher than the corresponding to pure HDPE, as shown in the previous subsection. But also, the density of the BF is higher than the pure HDPE one. This causes the calculated impacts of the injection processes and the End of Life to be higher due to the greater weight of the mounting sleeves with BFs.

Although the environmental impacts per kg were lower as the BF content increased for third-generation fibers, the overall results are not better than the pure HDPE. This is caused by the fact that a higher BF content means that the component has a higher density and, therefore, a greater weight, meaning that the additional impacts of the injection process and end of life are higher than the reduction created by the use of the BFs. However, all the calculations were performed in this subsection considering that the mounting sleeve is produced with the same thickness, not taking advantage of the better mechanical properties. To have a more detailed analysis, these mechanical properties are considered in the following subsection.

3.4.3. Original scenario (pure HDPE) versus new compound scenarios. Optimized injected components

In subsection 3.3, it was explained that using BFs improves the mechanical properties of the compound. Therefore, less thickness is needed to obtain the same stiffness, reducing weight and environmental impacts. Table 11 shows the results of the injected components for both generations, adjusting the thickness of the component to provide the same stiffness.

As expected, considering previous results, despite the lower thickness, the mounting sleeves with the second-generation fiber still generate higher environmental impacts in both ReCiPe and Carbon Footprint than the original HDPE component, even for the highest filler percentages. However, the results are much better for the third-generation BFs. With percentages of 20 wt % of fiber or higher, the environmental impacts of the mounting sleeves are lower for both environmental categories, showing the relevance of the higher mechanical properties and, therefore, the lower amount of material used.

Table 10
Results of impacts for injected components with the original thickness.

BF generation	Material	Total mass (g)	ReCiPe (mPt)	Carbon Footprint (kg eq. CO_2)
–	Pure HDPE	34.860	13.58	0.109
Second	HDPE +10 wt % BF	36.620	17.60	0.150
	HDPE +15 wt % BF	38.163	19.41	0.169
	HDPE +20 wt % BF	38.501	20.65	0.183
	HDPE +25 wt % BF	39.731	22.41	0.201
	HDPE +30 wt % BF	40.680	24.07	0.219
Third	HDPE +10 wt % BF	36.620	14.85	0.122
	HDPE +15 wt % BF	38.163	15.10	0.125
	HDPE +20 wt % BF	38.501	14.85	0.123
	HDPE +25 wt % BF	39.731	14.93	0.125
	HDPE +30 wt % BF	40.680	14.89	0.125

3.4.4. Detailed environmental impact of the selected component

Table 11 shows that the best environmental results are obtained for the 30 wt % third-generation fiber. For that compound, a detailed profile of the impact of the optimized mounting sleeve is provided in Table 12. It is observed that most of the environmental impact (66.9% under ReCiPe methodology and 61.1% under Carbon Footprint) is created by the compound material used. The injection molding process of the mounting sleeve is also quite relevant, showing 30.4% of the overall impact under ReCiPe and 35.6% under Carbon Footprint. Finally, the end of life increases the overall impact slightly, representing 2.6 and 3.3%, respectively.

Regarding the compound material, which is the main aim of this paper, it is shown that BFs create low environmental impact, as its obtaining, considering extraction, combing, cutting, and sieving, only create (for a component with 30 wt % fiber content) a 4.4% and 4.8% of the impact calculated under ReCiPe and Carbon Footprint, respectively. Transportations of the fibers also imply low impacts. However, the matrix of HDPE creates most of the impact of the component (51.4% and 44%, respectively), and the compounding process also represents a relevant amount, approximately 10%, under both methodologies.

This shows that the BF obtained in the third generation creates lower environmental impacts, even when the matrix is made of HDPE, a relatively low environmental impact polymer. Therefore, showing that BFs could help to substantially reduce the environmental impact of technical polymers, even when used in lower filler percentages.

4. Conclusions

The effects on the environmental impact produced by the treatment and processing of BF using an innovative and patented automated fiber extraction machine have been evaluated to obtain HDPE compounds reinforced with BF. The new HDPE compounds reinforced with BF were developed for the injection molding of components with lower environmental impacts. Two primary BF obtaining processes were compared: one with chemical treatment (2nd generation: extraction, natural drying, cutting, sieving, chemical treatment, and drying) and another one with a combing process that replaces the chemical treatment (3rd generation: extraction and combing, natural drying, cutting, and sieving). The combing process allows maintaining similar mechanical properties of the fiber compared to the treated one but also reduces the processes needed and, therefore, the corresponding environmental impacts. Compounding materials with 10, 15, and 20 wt % 3rd generation BF were produced by compounding extrusion. These materials were injected and characterized in terms of thermal and mechanical behavior.

Additionally, the compounds were also injected to produce mounting sleeves, a case study component originally manufactured with pure HDPE. These case study components were experimentally tested (stiffness test) to compare the mechanical results. Using the previous results and finite element analysis, a thickness optimization of the mounting sleeves was carried out to find the thickness required for each compound material to obtain the same stiffness as the original component (pure HDPE). This optimization study was also carried out for higher fiber contents (25 and 30 wt %), but the results were estimated based on the available experimental data for lower fiber percentages (10, 15, and 20 wt %). Since higher BF contents provide better mechanical properties, the thickness of the case study components was reduced as the BF percentage increased.

Table 11
Results of impacts for optimized injected components.

BF generation	Material	Volume (cm^3)	Thickness (mm)	Total mass (g)	ReCiPe (mPt)	Carbon Footprint (kg eq. CO_2)
–	Pure HDPE	41.17	3.50	34.860	13.58	0.109
Second	HDPE +10 wt % BF	39.40	3.35	35.049	16.85	0.144
	HDPE +15 wt % BF	37.18	3.17	34.468	17.53	0.152
	HDPE +20 wt % BF	35.87	3.06	33.547	17.99	0.159
	HDPE +25 wt % BF	34.99	2.99	33.762	19.04	0.171
	HDPE +30 wt % BF	33.97	2.90	33.566	19.86	0.181
Third	HDPE +10 wt % BF	39.40	3.35	35.049	14.21	0.117
	HDPE +15 wt % BF	37.18	3.17	34.468	13.64	0.112
	HDPE +20 wt % BF	35.87	3.06	33.547	12.94	0.107
	HDPE +25 wt % BF	34.99	2.99	33.762	12.69	0.106
	HDPE +30 wt % BF	33.97	2.90	33.566	12.28	0.103

Table 12
Results of impacts for optimized HDPE +30 wt % BF injected component.

Process	ReCiPe (mPt)	ReCiPe (%)	Carbon Footprint (kg eq. CO_2)	Carbon Footprint (%)
Compound	8.221	66.9	0.0630	61.1
BF extraction and combing	0.254	2.1	0.0019	1.8
BF cutting and sieving	0.284	2.3	0.0031	3.0
Pure HDPE	6.311	51.4	0.0454	44.0
Transportations	0.177	1.4	0.0017	1.6
Compounding	1.195	9.7	0.0110	10.7
Injection	3.738	30.4	0.0367	35.6
End of Life	0.325	2.6	0.0034	3.3
TOTAL	**12.284**	**100**	**0.1031**	**100**

On the other hand, an environmental analysis was carried out for both fiber generations (obtaining process). The 2nd generation fiber was an energy intensive process and created high environmental impacts (805.9 mPt and 8.20 kg eq. CO_2 per kg of processed BF), which were more significant than HDPE (268.6 mPt and 1.93 kg eq. CO_2). However, the 3rd generation fiber, with an optimized obtaining process and much lower energy consumption (no chemical treatment and subsequent drying), generated lower impacts (53.43 mPt and 0,50 kg eq. CO_2 per kg of processed BF). Therefore, optimizing the fiber obtaining process is crucial for the environmental impact. In the case of banana fiber, chemical treatments are processes to be avoided due to their higher energy consumption. Instead, other cleaner production processes, such as fiber combing, can be carried out with successful results, substantially reducing the environmental impact. Mechanical processes with low environmental impact, such as fiber combing, should be analyzed in other natural fibers to replace high-impact processes.

The environmental analysis of the subsequent compounding extrusion was also accomplished for all the BF generations (2nd and 3rd generations) and compounds (10, 15, 20, 25, and 30 wt % BF content with HDPE matrix). Compared to the pure HDPE original scenario, the impact of the compounds was lower for fiber weight percentages over 15% in ReCiPe and over 25% in Carbon Footprint (always with the 3rd generation fiber, since the 2nd generation has high impacts).

Additionally, the environmental analysis of the injection process of the mounting sleeves was carried out, both with the original and optimized thickness for each material. When keeping the original design, the impact was consistently higher in the compounding sleeves (regardless of the fiber content) than in the pure HDPE original component due to the higher density of the BF, which leads to higher impacts in the production and transportation (higher weights). However, if the thickness is optimized according to the material's mechanical properties, the mounting sleeves with more than 15 wt % of BF (3rd generation) had lower environmental impacts than the pure HDPE original component. In fact, the higher the BF content (3rd generation), the better the environmental results (with optimized thickness).

In the case of the 30 wt % BF (3rd generation) mounting sleeves (the best combination in terms of impact), most of the environmental impact created was due to the compounded material (66.9% under ReCiPe methodology and 61.1% under Carbon Footprint), while the injection molding process contributed to 30.4% of the overall impact under ReCiPe and 35.6% under Carbon Footprint. Most of the impact of the compounding material is generated by the HDPE matrix and the compounding process itself, showing that the 3rd generation fiber has an overall low environmental impact. It must also be noted that the compounding process requires pellet generation for the injection process, which adds a significant environmental impact. Therefore, the compounding with low fiber percentages is not considered adequate, as the additional compounding process generates more impact than the one that is avoided by substituting pure HDPE with BFs. It is worth noting that HDPE is a polymer with a relatively low environmental impact. This means that the results would be even better from an environmental perspective if the compound matrix were made out of another polymer with a higher environmental impact per kg (e.g., polyamides with 750–850 mPt and 8–9.5 kg eq. CO_2). In that case, environmental impact reductions could be achieved even with low filler percentages.

Finally, several future works could be explored to obtain banana fiber reinforced compounds with lower environmental impacts, as well as their possible industrial applications. The analysis of higher BF percentages could provide even lower environmental impacts, but mechanical behavior and reinforcement limits must be determined. Additionally, similar analysis should be performed with higher impact polymer matrices (such as PA 6, PA 6.6, PBT, etc.), as for those materials, higher environmental impact reductions are expected. As a third line of work, the energy consumption of the 3rd fiber generation could even be further reduced if a larger scale operation were to be carried out.

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CRediT authorship contribution statement

Pablo Bordón: Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Daniel Elduque:** Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Rubén Paz:** Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Carlos Javierre:** Methodology, Writing – original draft, Funding acquisition. **Dragan Kusić:** Validation, Investigation. **Mario Monzón:** Methodology, Conceptualization, Project

administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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