Research on the use of lignocellulosic fibers reinforced bio-polyamide 11 with composites for automotive parts: car door handle case study.

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Abstract

Most of the decisions taken during the early design and development steps of a new product compromise a large part of its cost, including its environmental footprint and energy consumption. This is of special interest for the automotive industry that has made an effort to increase its sustainability. Adjectives like bio-based, recyclable or biodegradable are commonly used as synonyms of greener; nonetheless, such materials must achieve the requirements of the industry. This paper researches the use of alternative materials instead of glass fiber reinforced polypropylene, a commodity material. The authors propose using a wood fiber reinforced polyamide 11 composite as replacement. The research discussed the mechanical properties of such composites, obtaining values similar to the currently used materials. Moreover, a case study was performed to assess the behavior of the composites when used to manufacture a door car handle. The materials with reinforcement contents ranging from 40 to 60% showed its ability to replace the commodity materials. Furthermore, a preliminary LCA analysis was performed to evaluate the environmental footprint of the researched materials. In was found, that, in terms of energy and carbon footprint, the PA11 composites were penalized by the energy cost of the PA11 monomer production.

Keywords: Natural fiber composites; Mechanical properties; Product design; bio polymers; automotive.

1 Introduction

The main objective in the research and development of new materials is its use by the industry. Due to the increased environmental awareness, nowadays a huge effort is devoted to substitute non-environmentally friendly materials by greener and sustainable alternatives (Mohanty et al., 2002; Serrano et al., 2014). One example is the replacement of synthetic reinforcement such as glass fibres (GF) by lignocellulosic materials (Kidalova et al., 2012). GF reinforced polyolefin are one of most commonly used composite materials, mainly due to its good ratio between mechanical properties and cost. Nonetheless, and although the 90% of composite materials are reinforced with GF, its recyclability is highly limited. Thus, their use in some fields like automotive industries has been reduced and these materials are being progressively replaced by cellulose fibres reinforced materials (Bledzki et al., 2006; George et al., 2016; Ribeiro et al., 2016; Thomason et al., 2016) which can be recycled and degraded (Holbery and Houston, 2006).

Biopolymers, bio-based and/or biodegradable polymers, are emerging as sustainable alternatives to oil-based polymers. Notwithstanding, to avoid redesigns, a substitutive material must show mechanical performance and other properties such as thermal stability or chemical resistance similar to the polymers to replace. Polyamide 11 (PA11) is a well stablished in the market since the 50's, totally bio-based polymer. PA11 has low 200ºC melting temperature, regarding other polyamides, that allows it being reinforced with natural fibres without any significant degradation of the cellulose (Oliver-Ortega et al., 2017; Zierdt et al., 2015). Although PA11 is not biodegradable, it, and its composites, can be recycled (Gourier et al., 2017). In addition, its non-biodegradable behaviour makes PA11 a promising alternative polymer for engineer applications were a long-time life span is desired: pipes, automotive field, biomedical applications, sports equipment, etc. (Devaux et al.; Meyer et al., 2002).

However, before the industrial use of PA11-based materials, an exhaustive study about its mechanical performance and processability is necessary. Sometimes, recyclability, ageing and life cycle studies are also required to assess if a bio-based material is greener than an oil-based counterpart (Corbière-Nicollier et al., 2001; Rebitzer et al., 2004). Mechanical and thermal properties of lignocellulosic fibres reinforced PA11 composites have been reported recently in the literature (Bourmaud et al., 2016; Oliver-Ortega et al., 2016b; Oliver-Ortega et al., 2017; Zierdt et al., 2015). Such studies showed that PA11-based composites reached mechanical properties comparable to GF reinforced polypropylene composites. Nonetheless, to the best knowledge of the authors, the industrial suitability of these PA11-based composites has not been reported.

In a case study, the material is applied to a specific part. The part is modelled and assayed under different loads by using a simulation software in order to check is competitiveness. Moreover, the design of the part can be modified during the process in order to improve its dimensional stability, ergonomics, etc. Later on, a prototype of the part is manufactured and mechanical tested in order to validate the obtained theoretical results. Nonetheless, the simulation procedure is quite important, as it reduces significantly the number of prototypes and its cost.

In this work, a car interior door handle, currently produced with a GF reinforced PP composite, was used as test case. The handle was measured to obtain a digital mock-up able to be submitted to finite element analysis. The use restrictions and loads were based on experimental measurements and human factors tables. A serie of tests were performed using the mechanical properties of the original materials and those of the proposed bio-based substitutes. The results were compared to assess witch materials satisfy the design requirements under normal and limit uses. Sets of PA11-based composites were proposed as possible replacements for PP-based materials. Finally, a preliminary life cycle analysis was carried out to sort the proposed materials from an environmental point of view. The sustainability of the materials was examined using the database included in the design software. The CO_2 fingerprint and energy consumption of the materials were estimated.

2 Materials and methods

1.1 Materials

The composites were formulated with a stone ground wood lignocellulosic reinforcement (SGW) and a bio-based polyamide 11 (PA11) matrix. The matrix was a commercial PA11 Rilsan® BMNO TL Polyamide 11, kindly supplied by Arkema S.A (Colombes, France). This matrix showed a density of 1.030 g/cm^3 and a melting temperature around 189ºC. Cellulose degrades when exposed to temperatures higher than 200ºC. Thus, the proposed PA11 was considered adequate to prevent the degradation of the reinforcement during the mixing and injection processes.

The SGW reinforcement was supplied by Zubialde, S.A. (Aizarnazabal, Spain). This reinforcement is derived from softwood (Pinus radiata) and it is a widely available commercial product, usually devoted to papermaking.

1.2 Materials compounding

The composites were formulated at reinforcement contents ranging from 20 to 60% w/w, with 10%w/w increases. The compounding process was performed using a Gelimat kinetic mixer model G5S by Draiswerke (New Jersey, USA). The mixer was operated at 300 rpm during the matrix and reinforcement introduction. Afterwards the speed was raised up to 2500 rpm for 4 to 5 minutes, until a 200ºC temperature was achieved. Then the composite was discharged from the mixer.

Al the resulting blends were grounded in a knives mill, dried in a stove and stored at 80ºC for at least 24h before processing.

1.3 Composite processing

The samples for the tensile and flexural tests were mold injected in a Meteor 40 injection equipment by Mateu & Solé (Catalunya, Spain). At least ten specimens of each composite were obtained. The processing temperatures were 170, 185, and 200 ºC (for the three heating areas of the machine), corresponding the last to the injection nozzle. First and second pressures were 120 and 37.5 kgf/cm^2, respectively.

1.4 Mechanical characterization.

In agreement with the ASTM D618 standard, the specimens were stored in a Dycometal conditioning chamber at 23 ºC and 50% relative humidity for 48 h, previously to the tensile and flexural tests.

The tensile and flexural tests were carried out using an Universal testing machine supplied by IDMtest (Instron™ 1122, Mark-10 Corporation, Copiague, New York, NY, USA), equipped with a 5kN load cell. Young's modulus was obtained using extensometer.

The flexural specimens were tested under three points bending configuration according with ASTM D790 standard specifications.

Tensile, Young's modulus, flexural strength and deformation at the maximum load were obtained from an average of at least 5 samples.

1.5 Test case modeling and evaluation.

The test case was a car interior door handle. The part was measured with a coordinate measuring machine Mitutoyo Crysta Apex 544. Afterward, a digital mockup was built using SolidWorks CAD software by Dassault Systemes (France).

The use loads were obtained from human factors tables. The geometric constrains were based on the normal use of a car door handle.

The finite element analysis was carried out with the SolidWorks analysis package. The digital model was created with the intention to submit it to a finite elements analysis, and consequently some details as round edges were omitted (Serrano et al., 2014). The analysis was static, meshed using hexahedron elements. The initial mesh was refined until considered correct.

SolidWorks package integrates a LCA module that was used to perform the preliminar analysis and compare the environmental impact of GF and Wood fiber composites. It was supposed that the materials and the handle door were produced at Europe, and the part was used and recycled at Europe.

3 Results and discussion

3.1 Composite mechanical results

Table 1 shows tensile and flexural properties of the composite materials. In the table, σ_t^C and σ_f^C are the tensile and flexural strengths, respectively. E_t^C and E_f^C are the Young's and the flexural moduli, respectively. Finally, ε_t^C and ε_f^C are the strain at break under tensile and flexural loads, respectively. The table also shows the properties of glass fibre reinforced polypropylene composites, as these materials profusely used to manufacture car interior parts.

Table 1: Tensile and flexural properties of SGW reinforced PA11 and GF reinforced PP composites

	Tensile			Flexural		
Sample	σ_t^C (MPa)	E_t^C (GPa)	ε_t^C (%)	σ_f^C (MPa)	E_f^C (GPa)	ε_f^C (%)
PA11	38.3 ± 0.9	1.4 ± 0.1	25.0 ± 1.6	40.0 ± 1.5	0.9 ± 0.1	7.4 ± 0.2
PA11+20SGW	45.0 ± 0.8	2.5 ± 0.1	9.5 ± 0.8	55.0 ± 2.2	1.7 ± 0.1	6.4 ± 0.2
PA11+30SGW	52.4 ± 0.8	3.0 ± 0.1	5.5 ± 0.4	68.7 ± 1.8	2.1 ± 0.1	5.8 ± 0.2
PA11+40SGW	56.7 ± 0.6	3.9 ± 0.1	4.5 ± 0.3	77.5 ± 1.3	2.9 ± 0.2	5.2 ± 0.2
PA11+50SGW	63.9 ± 1.8	4.8 ± 0.1	3.7 ± 0.2	92.6 ± 3.1	3.3 ± 0.2	4.2 ± 0.1
PA11+60SGW	59.6 ± 2.1	5.8 ± 0.2	2.8 ± 0.2	102.7 ± 4.8	4.1 ± 0.3	3.2 ± 0.1
PP	27.6 ± 0.5	1.5 ± 0.1	9.3 ± 0.2	40.2 ± 0.5	1.1 ± 0.1	-
PP+20GFs	50.9 ±4.3	4.6 ± 0.1	3.1 ± 0.1	78.0 ± 0.9	3.2 ± 0.1	-
PP+30GFs	58.5 ± 4.3	5.9 ± 0.2	3.0 ± 0.2	88.1 ± 2.5	4.7 ± 0.2	-
PP+20GFe	67.6 ± 0.9	4.5 ± 0.2	4.7 ± 0.2	94.8 ± 2.2	3.2 ±0.2	-
PP+30GFe	79.6 ± 1.2	6.0 ± 0.1	4.4 ± 0.2	109.8 ±2.8	4.7 ± 0.1	-

The tensile properties of the PP-based composites were obtained from the literature (Julian et al., 2012; Lopez et al., 2013; Lopez et al., 2011; Lopez, Joan P. et al., 2012). All the composites showed increased properties when the reinforcement content was increased. Previous researches showed that it is possible to reinforce PA11 with lignocellulosic fibers without the addition of coupling agents (Gourier et al., 2017; Oliver-Ortega et al., 2016a; Oliver-Ortega et al., 2016b; Oliver-Ortega et al., 2018; Zierdt et al., 2015). Composites with SGW contents higher than 60% w/w showed fluencies lower than the required for its mold injection.

The strengths and the moduli (tensile and flexural) evolved linearly against 10% to 50% w/w fiber contents. This can be an indicative of: i) good dispersion of the reinforcement in the matrix and ii) the existence of an interphase that allow transferring loads from the matrix to the reinforcement. The maximum value of the tensile and flexural strengths of PA11 composites reinforced with a 50% SGW were 63.9 and 92.6MPa, respectively.

The tensile strengths of the composites with 60%w/w of SGW decreased indicating a possible creation of fiber bundles or difficulties to obtain good dispersions for high reinforcement contents. The flexural strength increased but with less impetus. Nonetheless, the moduli of the composites showed its maximum value for the 60% w/w SGW content. The enhancements, regarding the polymer matrix, were 314% and 355% for the tensile and flexural moduli.

Figure 1 shows the behavior of the tensile strength of PA11 composites regarding its fiber content. In addition, the values of PP-GF coupled and sized composites are included for comparison purposes. The PA11 matrix has a higher tensile strength than the PP matrix. However, PP-GF composites increase their strength quicker than the PA11-based materials. This fact is clearly reflected by the slope of the regression lines. Thus, GF has a higher strengthening impact that SGW. Nevertheless, this result was expected due to the high mechanical properties of GF (Lopez, Joan P. et al., 2012; Lopez, J. P. et al., 2012; Reixach et al., 2013). Thus, higher SGW contents are needed to obtain similar properties than GF-based composites.. The differences between the GF composites are related with the strength of the interface between the GF and the matrix. The flexural strength showed a similar behavior.

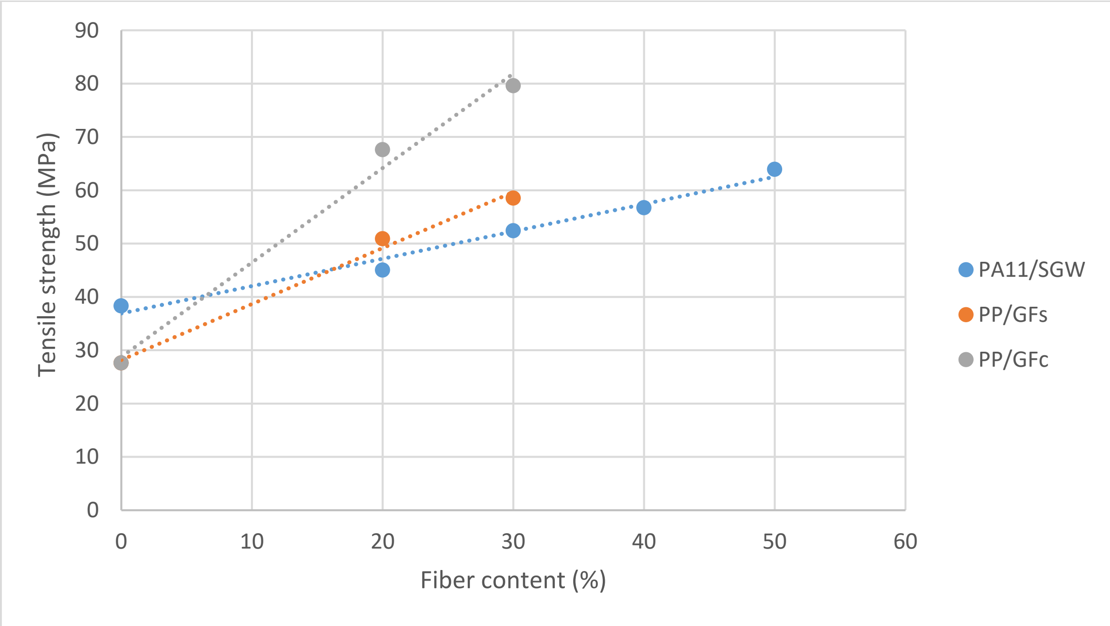

Figure 1. Tensile strength of PA11/SGW composite materials in comparison with PP/GF composites

In the case of the Young's modulus (Figure 2), PA11 and PP have similar moduli. Nonetheless, the reinforcement impact of SGW fibers is lower than GF, due to its lower intrinsic modulus. However, the strength of the interface has a limited impact on the modulus of the composites. Thus, GF sized and coupled showed almost the same results.

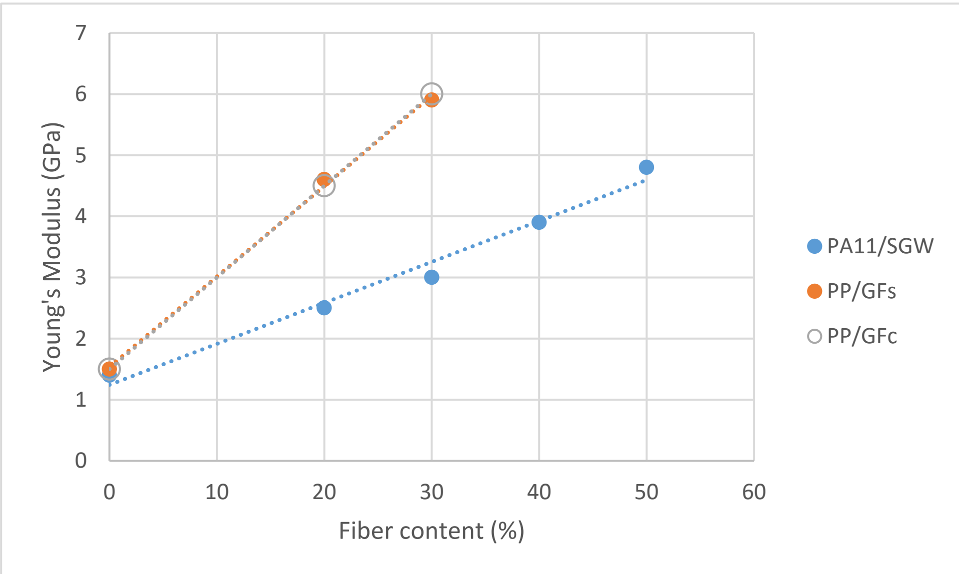

Figure 2. Tensile modulus of PA11/SGW composites and its comparison with PP/GF composites

Nonetheless, table 1 shows that PA11-based composites with high percentages of SGW reinforcements obtained similar strengths and moduli than some PP/GF composites. Furthermore, the density of SGW is much lower than GF's and therefore, the PA11+SGW composites are expected to show better specific properties at the same reinforcement contents (Reixach et al., 2015).This is especially interesting to the automotive industry, where the research towards lighter components is very active (Bledzki et al., 2006; Holbery and Houston, 2006). Therefore, from a mechanical properties point of view it is possible to substitute some PP/GF composites by PA11/SGW materials. Nonetheless, a test case was considered interesting to explore the behavior of the composites.

3.2 Case study definition

A car door interior handle was used for the case study. On the one hand, the automotive industry was considered appropriate because it is increasingly showing its interest towards sustainability and recyclability (Schöggl et al., 2017). Automotive industry is also an economic sector with high global representativeness. On the other hand, PP+GF composites are commodity materials for the automotive industry, mainly due to its competitive mechanic properties and cost. Nonetheless, such materials show poor recyclability due to the increasing shortening of GF when reprocessed (Oliver-Ortega et al., 2016b; Oliver-Ortega et al., 2018).

The researchers looked for a car component manufactured by mold injection and PP+GF. Another requirement for the test case was being easily recognizable and with well stablish operating conditions. The car interior door handle was considered representative as it is a well-known component present in all the cars, with recognizable and easy to stablish use conditions. Figure 3 shows some door handles from different cars models.

Figure 3. Some examples of car interior door handle.

Although the differences in the colours and the grips, all the car handles are based on a similar design, showing the maturity of the concept. Some changes in the measurements or proportions can be observed, but at the end, the handles are very similar. These handles are used with the fingers and thus, the anthropometry of the human hand has a major role to define the geometry of these components.

Figure 4, shows the digital mock-up of the test case. The figure also shows constrains and loads.

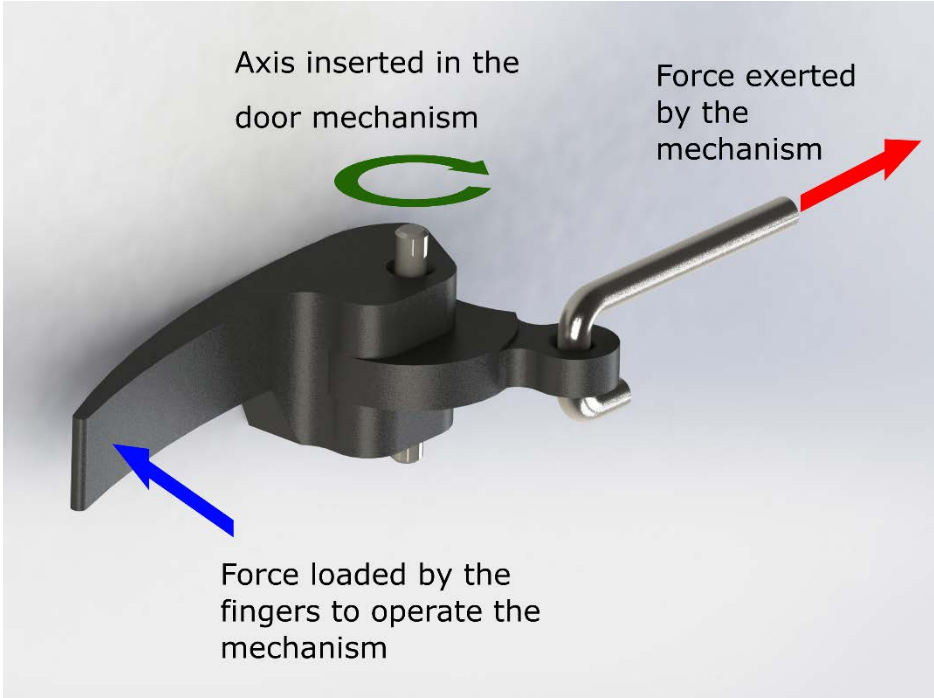

Figure 4: Render of the digital mock-up of the test case and the expected constrains and loads

The doors handle revolves around the axis when the user applies a load using its fingers. This movement operates a wire connected to the door mechanism. The wire is usually under tensile loads ensuring the return of the handle to the rest position when the user stops applying any load. The reference model was made of a 20% w/w GF reinforced PP composite. This information was engraved in the original mold injected part. Nonetheless, the information did not specify the type of GF.

The force required to operate the mechanism was measured by means of a dynamometer at different car doors. After multiplying the highest obtained value by a 1.5 factor and round the result it was stablished that any car door handle will operate always under 20N loads. Nonetheless, missuses of the handle were also to be considered. The literature shows that it is possible to exert a 70N force with two fingers (DTI, 2002). Both loads were used during the analysis of the test case.

3.3 Test case analysis

As it was established in the methods section, the finite element analysis was carried out with the advanced simulation package the SolidWorks CAD/CAE version 2018. The movement constrains were applied to the model by limiting the movement of the axis hole to rotations along the Z axis. The finger's user loads were applied to the grip zone of the handle. Then, the movement of the hole, intended to connect with the wire, was limited in all the directions, making the model static (Figure 5)

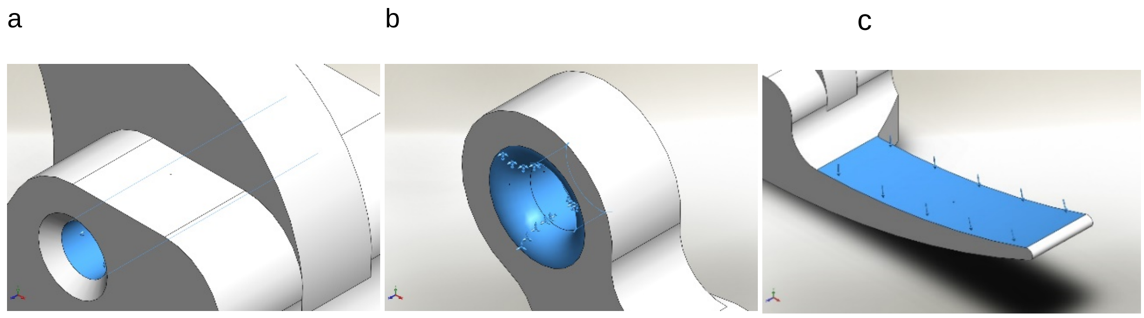

Figure 5: Loads and constrains applied to the model: a: hinge constrain in the axis zone, b: total restriction of movements and rotations in the plug zone, c: finger loads in the grip zone.

The model was meshed with 8235 standard quad 4-point elements, with mean 2.3 mm size and a 0.11 tolerance. The 98.4% of the elements showed aspect ratios under 3, and only 0.05% of the rest of the elements showed aspect ratios over 10.

The analysis was carried out for all the materials presented in table 1, which includes PA11 and PP based composites with different percentages of reinforcement. Two different loads were stablished for the test: a load of 20 N as normal use; and 70 N as limit use or misuse. The collected results were the von Mises strengths (MPa), net displacements (mm), percentage displacements (%) and the safety factor.

Moreover, the software returned visual and numeric results. Figure 6 shows some of the results obtained for a door handle manufactured with a PA11+50SGW material under normal use conditions (20N).

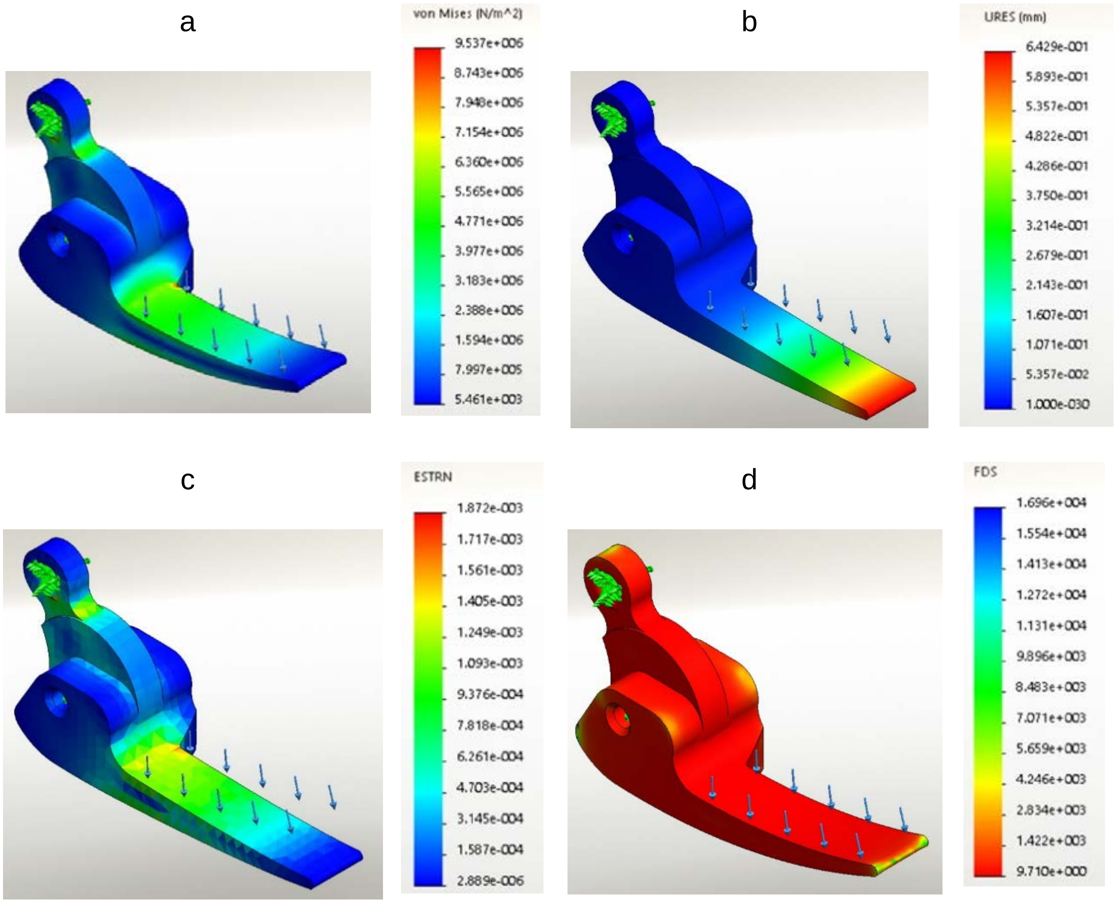

Figure 6: Graphic output summaries of the finite element analysis of a PA11+50SGW door handle under normal use conditions; a: von Mises strengths, b: net displacements, c: strain, d: security factor.

Figure 6A shows the von Mises stress. The maximum values are located at the end of the grip zone. In this zone, the shape of the handle increases its section. In order to simplify the modes some of the edge rounding were omitted. Thus, these maximum values correspond to a stress multiplication phenomena not present in the final part due to the presence of edge rounding. The grip shows also a neutral zone in blue coloring and the upper and lower areas under stress. Due to the loads, the region in contact with the fingers will be under tensile and the upper region under compression. The grip coincides with a cantilever beam under a distributed load scheme. The central zone, being the thickest, is under low stresses. The third zone coincides with the cable attachment. The highest stresses coincide with the lower area zone and are in the order of 3 to 6 MPa. The scheme coincides with a cantilever beam with a located load.

Figure 6B shows the displacements. The grip zone shows a progressive deformation from the handle body to its end. This is in agreement with the cantilever beam scheme. The maximum displacement below 1mm. The rest of the part shows much lower displacements. The predicted displacements do not affect the functionality of the part. Thus, no further stiffening is required.

Figure 6C shows the internal strains. In general, these strains coincide with the stresses. The figure can help identifying the areas prone to collapse. The higher strains coincide with the areas under tensile and compression in the grip and the neck zone of the cable attachment. Anyhow, none of the zones are previewed to collapse or develop fractures.

Figure 6D Shows the value of the safety factor, understood as the ratio between the tensile strength and the current load. The minimum safety factor was 9.7, leaving a comfortable safety margin. The part is almost painted in the same color showing an equilibrated design

The same analyses were carried out using the mechanical properties of all the composites. The objective of such analysis was identifying the composites able to substitute the PP+20GF. Thus, the results obtained by such materials were used to define boundary conditions.

Car door handles are exposed to break under use if the maximum tensile strength of the material is reached. The safety factor gives an idea of how far is the probability of collapse. Thus, the safety factors obtained by the GF-based composites were proposed as goals in this study. On the other hand, the handles are exposed to deformation. A component showing high deformations can be unable to fulfil its function. Thus, the deformation and strains showed by the GF-based composited were taken also as reference.

The part was tested under 70N, the maximum force that an adult can made with the fingers in a similar movement as the performed to open the cars door through the handle (DTI, 2002). In this case, the primary concern was the ability of the part to deform without breaking, and the safety factor was established as main parameter. Table 2 shows the outputs.

Table 2: Main outputs of the analysis of the test case under 70 N loads.

Material	Safety factor	Deformation (mm)	Strain (%)	Von Mises (MPa)
PP	1.2	6.8	1.8	33.73
PP+20GFs	2.3	2.3	0.6	33.71
PP+30GFs	2.6	1.6	0.4	33.68
PP+20GFc	2.8	2.3	0.6	33.71
PP+30GFc	3.6	1.6	0.4	33.68
PA11	1.2	8.3	2.4	33.52
PA11+20SGW	1.6	4.4	1.3	33.53
PA11+30SGW	2.1	3.6	1.0	33.21
PA11+40SGW	2.3	2.6	0.8	33.47
PA11+50SGW	2.8	2.3	0.7	33.46
PA11+60SGW	3.1	1.8	0.5	33.44

Von Mises strengths showed little oscillations when different materials were tested. On the other hand, the deformations and the strains changed a lot from one material to the other. This was expected as the moduli of the materials showed also significantly different values. As expected, the higher the modulus, the lower the deformation or the strain.

The safety factor showed by the composites reinforced with a 20% of GF was in the range from 2.3 to 2.8. In a first hypothesis, these values were rounded to the lower integer and safety factors. Thus, safety factors lower than 2 were considered inappropriate to ensure a correct deployment of the component. Usually the safety factors are integers used to minorise the properties of the materials or increase the loads. A safety factor with a value of 2 is usual in engineering calculations. All the PA11-based composites with SGW contents higher than 20% w/w were considered suitable. Nonetheless, a more restricted lecture of the data positions the cutting value at 2.8, obtained for the PP+20%GFc. This value restricts the election to the composites with SGW contents higher than 40% w/w (Figure 5).

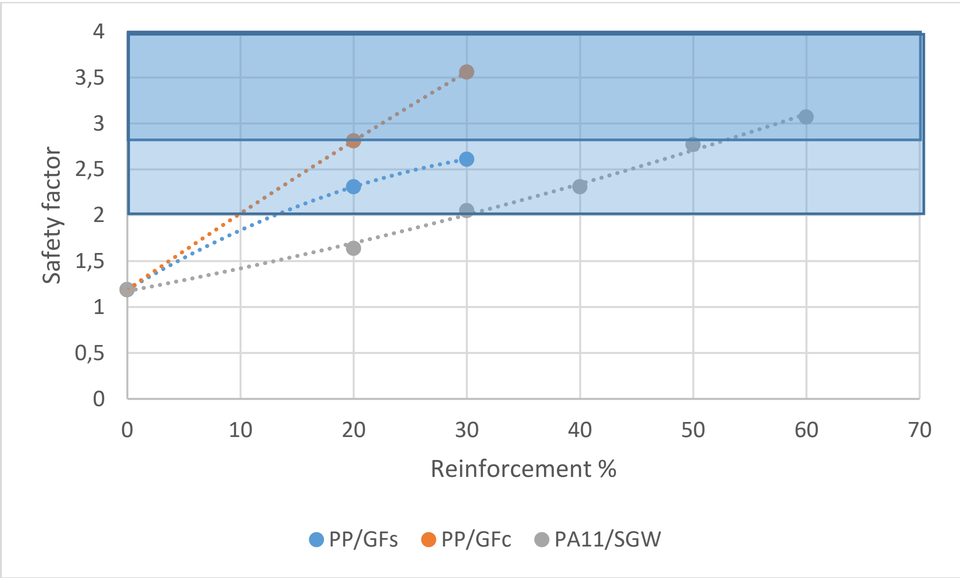

Figure 7: Zones defining the materials that meet the safety factor criteria.

Figure 7 shows the evolution of the safety factors of the part against the reinforcement content. The shaded areas indicate the safety factors higher than 2 or 2.8. Thus, the materials zones represented by the shaded rectangles show the materials that fulfil the minimum safety factor criteria. It was found that the matrices showed safety factor near one, showing ineffective to be used without reinforcement.

The maximum deformations of the parts manufactured with materials that fulfilled safety factors above 2 were inferior to 4 mm. Nonetheless, If the most restricted criteria is applied, the deformation values were similar for all the suitable materials. The strains remained always below or equal to 1% applying the less strict criteria.

The next step was testing the components under normal use. Undoubtedly, the safety factors were expected to be noticeably superior and the criterion was replaced by the maximum deformation. Table 3 shows the obtained results.

Table 3: Main outputs of the analysis of the test case under 20 N loads.

Material	Safety factor	Deformation (mm)	Strain (%)	Von Mises (MPa)
PP	4,2	1,9	0,5	9,62
PP+20GFs	8,1	0,6	0,2	9,61
PP+30GFs	9,1	0,5	0,1	9,61
PP+20GFc	9,8	0,7	0,2	9,61
PP+30GFc	12,4	0,5	0,1	9,62
PA11	4,2	2,4	0,7	9,56
PA11+20SGW	5,8	1,3	0,4	9,55
PA11+30SGW	7,2	1,0	0,3	9,54
PA11+40SGW	8,2	0,7	0,2	9,53
PA11+50SGW	9,7	0,6	0,2	9,54
PA11+60SGW	10,8	0,5	0,2	9,54

As expected, the safety factor has increased significantly in all the cases while the Von Mises strength decreased. The safety factor showed under normal conditions were higher than 4 in all the cases, including the matrices. Thus, this criterion was not considered relevant for normal conditions case.

All the GF-based components showed deformations less than 1mm,with a minimum deformation of 0.5mm for the PP+30%GF composites.. Under these criteria, the suitable PA11-based composites included only those with contents higher than 50% w/w contents or those with 30% w/w contents or superior. Figure 8 shows the zones defined by the maximum deformation criteria.

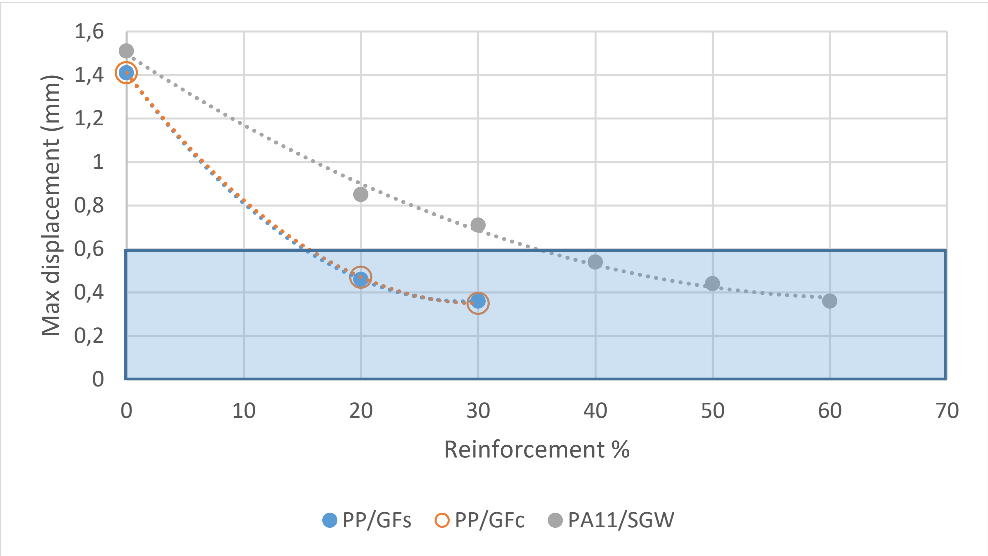

Figure 8: Zones defining the materials that meet the maximum displacement criteria.

In the figure, the deformations obtained with the GF-based composites almost coincide due to their similar moduli. The maximum deformation was limited to 0.6 mm. The composites with SGW contents higher that 40% w/w fulfilled the criteria.

Figure 9 shows a combination of criteria, safety factor and maximum displacement.

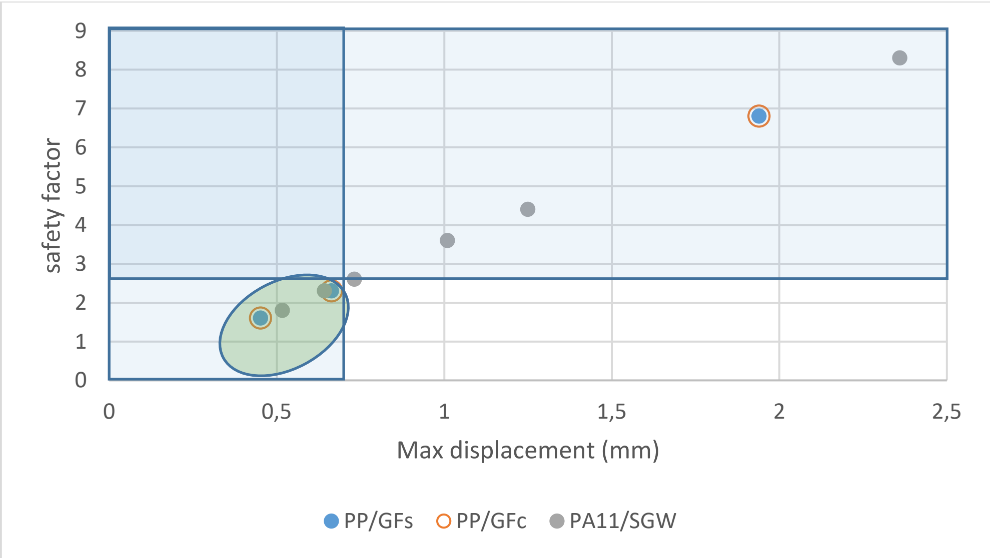

Figure 9: Zone diagram with the materials fulfilling the safety factor and maximum displacement criteria.

The zone defined by the materials that fulfil all the applied criteria enclosed the materials with SGW contents equal or superior to 40% w/w.

Having in account that the component has a volume of 11.3 cm3, table 4 shows the density of the composites and the final mass of the components.

Table 4: Densities of the composites and mass of resulting the car door handle

Material	Density (g/cm^3)	Component mass (g)
PP+20GF	1.04	11.8
PP+30GF	1.12	12.7
PA11+40SGW	1.15	12.9
PA11+50SGW	1.18	13.3

PA11+60SGW	1.22	13.8

The PA11+SGW materials proposed as replacement of PP+GF composites showed higher densities, and consequently the mass of the parts produced with such materials will be heavier. The main reason is the presence of a higher amount of reinforcing fibers with a density higher than matrix's. The increases were noticeable and found to be 9.3%, 12.7% and 16.9% for the composites reinforced with 40, 50 and 60%w/w of SGW, respectively.

3.4 Preliminary LCA

The finite element analysis showed that PA11/SGW bio-based composites were able to substitute materials based on an oil-based matrix and a mineral reinforcement. However, the resulting parts were heavier than the reference. Nonetheless, bio-based composites are expected to show a lower environmental impact than oil-based ones. Taking advantage of the Sustainability package of Solid Work and information provided by the PA11 producer, a preliminary LCA was carried out (Devaux et al.; Meyer et al., 2002).

The parts were supposed to be fabricated and used in the European Union. The lifespan was established at 10 years and the means of transport were 100% trucks with a mean displacement of 1900 km.

At the end of its lifespan, the PP+GF components are incinerated and dumped at the same amount, as PP-GF composites cannot be recycled. In the case of the PA11-based composites it was assumed that the recyclability potential allowed a 60% recycling, 30% incinerating and 10 % dumping hypothesis.

The first analysis performed was the total energy consumed during the cycle (Figure 10).

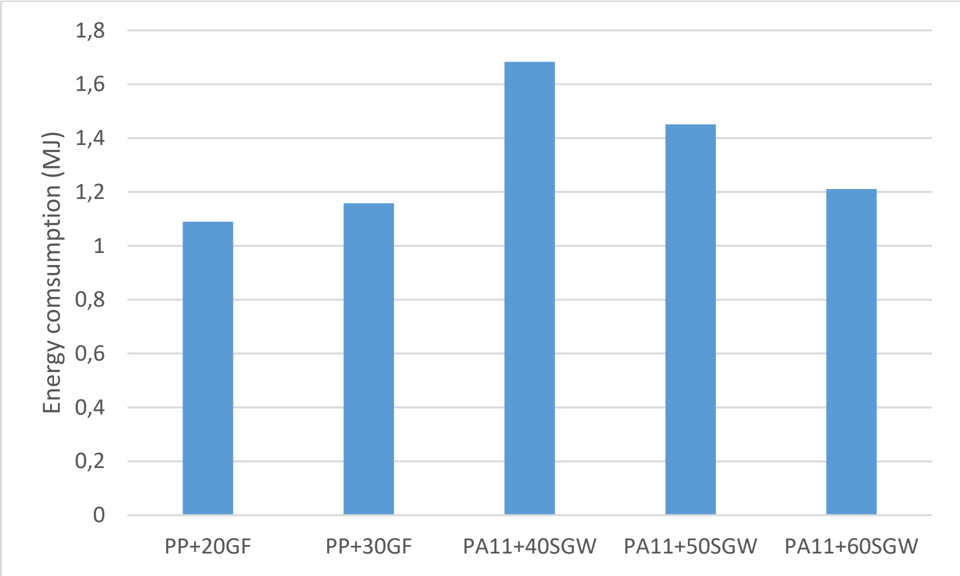

Figure 10: Energy consumption total for a 10 year lifecycle.

The analysis showed that the energy expended by the PA11-based composites was superior to those PP-based. The reason is the industrial process to obtain the PA11. The monomer of PA11 production from the raw material (castor oil) has a high energy cost regarding the production of polyolefin monomers. However, the synthesis route is similar to some oil-based monomers, highly studied and optimized. This is prone to occur for the case of products derived from castor oil due to the important platform of organic chemical compounds that represents this oil. Nonetheless, the composites adding higher percentages of reinforcement showed energy consumptions similar to the PP-based materials. Thus, from an energy point of view PA11+60SGW composite is the most convenient.

Another data to consider when environmental impact of a product is evaluated is the carbon footprint. Figure 11 shows the carbon footprints.

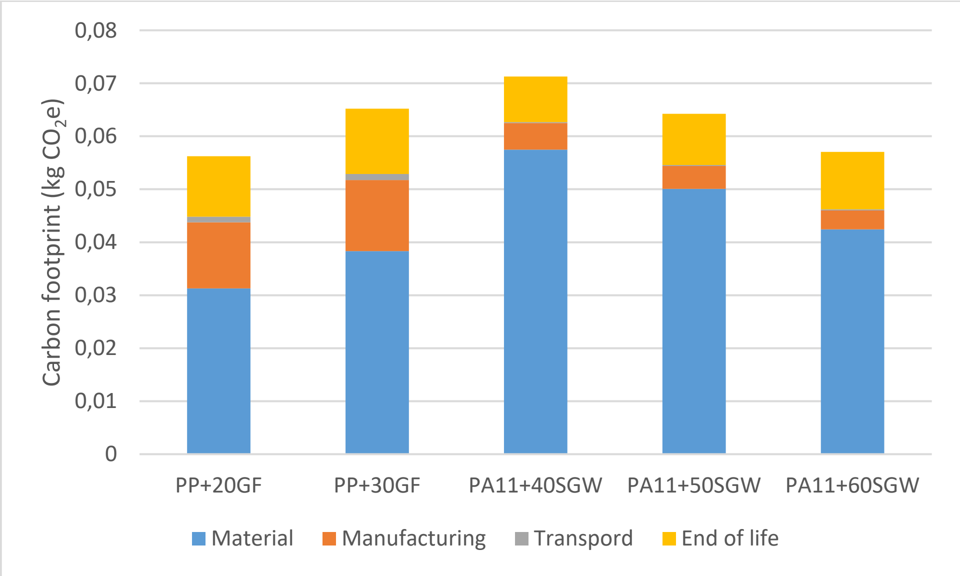

Figure 11: Carbon footprint for a handle in a lifespan of 10 years.

PA11-based composites were, again, highly penalized by the energy needed to obtain the matrix. Although this higher CO_2 emission, related mainly with the energy consumption for the material production, in the other parameters studied, PA11 returned lower environmental impacts, showing the sustainability of these compounds. The figure shows that a PA11+60SGW composite generate a carbon footprint similar to a PP+20GF composite.

4 Conclusions

Composite materials based on a PA11 matrix reinforced with stone grounwood were formulated, manufactured and tested. These composite materials were totally bio-based.

The mechanical properties of these bio-based composites were compared to PP+GF commodity materials used in the automotive industry. At the higher SGW contents, the macro-properties of both composites were similar and reached similar tensile and flexural strengths as like as similar Young's and flexural moduli. Nonetheless, the specific properties of the PA11-based materials were penalized by the high density of this matrix.

A case study consisting in a car interior door handle was performed. The test case was based on an original part manufactured with a PP+20GF composite. The part was assayed under normal and limit conditions. A finite element analysis was used for this purpose. The analysis showed that PA11-based materials with SGW contents equal or higher than 40% w/w delivered safety factors and maximum deformations similar to the original component.

Later on, a preliminary life cycle analysis showed that PA11-based composited consumed higher amounts of energy than the PP-based ones. Nonetheless, the energy consumptions were similar to a PP-based composite with a 30% w/w GF content. The rest of PA11-based composites needed noticeably higher amounts of energy.

A study of the carbon footprint of the composites showed that composites with 60% w/w SGW content had a footprint similar to a PP-based composite with a 20% w/w GF content.

From mechanical and environmental impact points of view only the materials with higher natural fiber contents showed fitted to replace a PP-based composite. Nonetheless, much more research is needed to decrease the energy consumption necessary to manufacture PA11, otherwise its bio-based advantages are somehow obscured.

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References

Bledzki, A.K., Faruk, O., Sperber, V.E., 2006. Cars from bio-fibres. Macromolecular Materials and Engineering 291(5), 449-457.

Bourmaud, A., Le Duigou, A., Gourier, C., Baley, C., 2016. Influence of processing temperature on mechanical performance of unidirectional polyamide 11–flax fibre composites. Industrial Crops and Products 84, 151-165.

Corbière-Nicollier, T., Gfeller Laban, B., Lundquist, L., Leterrier, Y., Månson, J.A.E., Jolliet, O., 2001. Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics. Resources, Conservation and Recycling 33(4), 267-287.

Devaux, J.-F., Lê, G., Pees, B., Application of Eco-Profile Methodology To Polyamide 11. Arkema, unpublished (www. arkema. com/pdf/EN/products/technical_polymers/rilsan/rilsan_website_2011/rilsan_ecoprofile_article. pdf).

DTI, 2002. Strength data for design safety, in: Industry, D.o.t.a. (Ed.). London.

George, M., Chae, M., Bressler, D.C., 2016. Composite materials with bast fibres: Structural, technical, and environmental properties. Progress in Materials Science 83, 1-23.

Gourier, C., Bourmaud, A., Le Duigou, A., Baley, C., 2017. Influence of PA11 and PP thermoplastic polymers on recycling stability of unidirectional flax fibre reinforced biocomposites. Polymer Degradation and Stability 136, 1-9.

Holbery, J., Houston, D., 2006. Natural-fiber-reinforced polymer composites in automotive applications. JOM 58(11), 80-86.

Julian, F., Mendez, J.A., Espinach, F.X., Verdaguer, N., Mutje, P., Vilaseca, F., 2012. Bio-based composites from stone groundwood applied to new product development. BioResources 7(4), 5829-5842.

Kidalova, L., Stevulova, N., Terpakova, E., Sicakova, A., 2012. Utilization of alternative materials in lightweight composites. Journal of Cleaner Production 34, 116-119.

Lopez, J.P., Girones, J., Mendez, J.A., Pelach, M.A., Vilaseca, F., Mutje, P., 2013. Impact and flexural properties of stone-ground wood pulp-reinforced polypropylene composites. Polymer Composites 34(6), 842-848.

Lopez, J.P., Mendez, J.A., El Mansouri, N.E., Mutje, P., Vilaseca, F., 2011. Mean intrinsic tensile properties of stone groundwood fibers from softwood. BioResources 6(4), 5037-5049.

Lopez, J.P., Mendez, J.A., Espinach, F.X., Julian, F., Mutje, P., Vilaseca, F., 2012. Tensile Strength characteristics of Polypropylene composites reinforced with Stone Groundwood fibers from Softwood. BioResources 7(3), 3188-3200.

Lopez, J.P., Mutje, P., Pelach, M.A., El Mansouri, N.E., Boufi, S., Vilaseca, F., 2012. Analysis of the tensile modulus of PP composites reinforced with Stone grounwood fibers from softwood. BioResources 7(1), 1310-1323.

Meyer, A., Jones, N., Lin, Y., Kranbuehl, D., 2002. Characterizing and modeling the hydrolysis of polyamide-11 in a pH 7 water environment. Macromolecules 35(7), 2784-2798.

Mohanty, A.K., Misra, M., Drzal, L.T., 2002. Sustainable bio-composites from renewable resources: Opportunities and challenges in the green materials world. Journal of Polymers and the Environment 10(1-2), 19-26.

Oliver-Ortega, H., Granda, L.A., Espinach, F.X., Delgado-Aguilar, M., Duran, J., Mutjé, P., 2016a. Stiffness of bio-based polyamide 11 reinforced with softwood stone ground-wood fibres as an alternative to polypropylene-glass fibre composites. European Polymer Journal 84, 481-489.

Oliver-Ortega, H., Granda, L.A., Espinach, F.X., Mendez, J.A., Julian, F., Mutjé, P., 2016b. Tensile properties and micromechanical analysis of stone groundwood from softwood reinforced bio-based polyamide11 composites. Composites Science and Technology 132, 123-130.

Oliver-Ortega, H., Méndez, J.A., Mutjé, P., Tarrés, Q., Espinach, F.X., Ardanuy, M., 2017. Evaluation of thermal and thermomechanical behaviour of bio-based polyamide 11 based composites reinforced with lignocellulosic fibres. Polymers 9(10), 522.

Oliver-Ortega, H., Méndez, J.A., Reixach, R., Espinach, F.X., Ardanuy, M., Mutjé, P., 2018. Towards More Sustainable Material Formulations: A Comparative Assessment of PA11-SGW Flexural Performance versus Oil-Based Composites. Polymers 10(4), 440.
Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment International 30(5), 701-720.
Reixach, R., Espinach, F.X., Arbat, G., Julián, F., Delgado-Aguilar, M., Puig, J., Mutjé, P., 2015. Tensile Properties of Polypropylene Composites Reinforced with Mechanical, Thermomechanical, and Chemi-Thermomechanical Pulps from Orange Pruning. BioResources 10(3), 4544-4556.
Reixach, R., Franco-Marquès, E., El Mansouri, N.-E., de Cartagena, F.R., Arbat, G., Espinach, F.X., Mutjé, P., 2013. Micromechanics of Mechanical, Thermomechanical, and Chemi-Thermomechanical Pulp from Orange Tree Pruning as Polypropylene Reinforcement: A Comparative Study. BioResources 8(3), 3231-3246.
Ribeiro, M.C.S., Fiúza, A., Ferreira, A., Dinis, M.D.L., Meira Castro, A.C., Meixedo, J.P., Alvim, M.R., 2016. Recycling Approach towards Sustainability Advance of Composite Materials' Industry. Recycling 1(1), 178.
Schöggl, J.-P., Baumgartner, R.J., Hofer, D., 2017. Improving sustainability performance in early phases of product design: A checklist for sustainable product development tested in the automotive industry. Journal of Cleaner Production 140, 1602-1617.
Serrano, A., Espinach, F.X., Tresserras, J., Pellicer, N., Alcala, M., Mutje, P., 2014. Study on the technical feasibility of replacing glass fibers by old newspaper recycled fibers as polypropylene reinforcement. Journal of Cleaner Production 65, 489-496.
Thomason, J., Jenkins, P., Yang, L., 2016. Glass Fibre Strength—A Review with Relation to Composite Recycling. Fibers 4(2), 18.
Zierdt, P., Theumer, T., Kulkarni, G., Däumlich, V., Klehm, J., Hirsch, U., Weber, A., 2015. Sustainable wood-plastic composites from bio-based polyamide 11 and chemically modified beech fibers. Sustainable Materials and Technologies 6, 6-14.