



Environmental Impact of Chicken Feathers Based Polypropylene Composites Developed for Automotive and Stationary Applications and Comparison with Glass-Fibre Analogues

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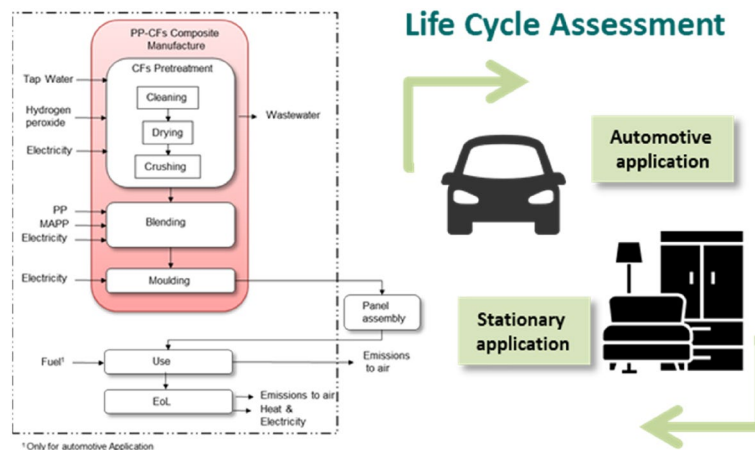
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Abstract

In last decades, there has been an interest in using biogenic wastes and by-products as fillers or reinforcements to produce polymer composites. Hence, new composites materials based on a blend of biogenic chicken feathers (CFs) and polypropylene (PP) are proposed in this work and compared, from the environmental point of view, with currently used materials as neat PP and PP reinforced with glass-fibres (PP-GF). A Cradle-to-Grave Life Cycle Assessment (LCA) was performed in order to compare the environmental impact of these three materials when being used either for automotive or stationary applications. The mechanical properties of each material were taken into account to calculate the equivalent mass of each industrial application and the use phase and end of life (EoL) were included in the LCA study. The results showed that, for automotive applications and for all the materials studied (PP-GF, PP-CFs and PP) the use phase has a great contribution to the environmental impact categories considered, proving that the new developed material based on CFs (PP-CFs) would be appropriate for stationary applications but not for mobile applications as automotive ones. In addition, the EoL scenario considered, i.e. incineration with energy recovery, has proven to provide extra environmental credits.

Graphical Abstract



Keywords Chicken feathers · Biocomposites · Biogenic waste · Life cycle assessment · Automotive sector

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Statement of Novelty

Life Cycle Assessment of novel chicken feathers based polypropylene composites for different applications pointed out the importance to consider mechanical properties when defining the functional unit in order to compare different materials for the same application.

Introduction

Composites materials are made by mixing two or more constituent materials with considerably different properties in order to generate a material with better characteristics compared to the individual constituents. Among them, it is worth to mention fibre reinforced polymer composites that are made up of fibres that carry the load and a polymeric matrix that wraps such fibres, distributes the stress, gives the reinforcement a solid shape, and protects them from environmental influences. Both fibres and matrices can be of natural or synthetic origin, being the natural ones those that pull research and market innovations due to environmental concerns [1]. Consequently, although synthetic fibres (glass and carbon) and synthetic matrices (thermosets and thermoplastics) are still predominant in composites [2], in some cases either the reinforcement or the matrix derive from natural resources, yielding to biocomposites. Such materials are scientifically and industrially becoming crucial to move towards a more sustainable approach [3–5]. Hence, novel industrial applications of biocomposites can be found currently in marine, automotive, construction, packaging and aerospace sectors [6].

Thinking closely about the automotive sector, it is moving forward to address the growing concern about environmental impacts due to related sectors, such as transportation. In the current times several innovations have involved the use of recycled and recyclable polymers, composites and biocomposites. It should be noted that the automotive industry is subject to social and political pressures to supply low-polluting vehicles with more recyclable parts and increased fuel efficiency. That is why, polymers (plastics) and polymer-matrix composites are widely used in the automotive sector, representing 9% of the vehicle weight [7]. In addition, since 2015, the 95% of the weight of a vehicle has to be recyclable, according to the European Guideline 2000/53/EG administered by the European Commission. Consequently, vehicles must be constructed of 95% recyclable materials, with 85% recoverable through reuse or mechanical recycling and 10% through energy recovery or thermal recycling.

Regarding polymers, polypropylene (PP) accounts for more than half of all the plastic materials used in

automobiles since it is a low-cost polymer with good mechanical properties and moldability [8]. Besides, the use of biocomposites in the automotive industry seems to be a real alternative to conventional materials in order to respond to social demands and environmental policies, and they have attracted an increasing interest of researchers for developing automotive components [9]. The most common strategy focuses on the substitution of inorganic fillers such as glass fiber (GF) with natural fibres (flax, hemp, sisal, jute, etc.) to reinforce polymeric matrices resulting, for example, in interior parts of a car such as front door linings, driver's seat backrest or door panels [10, 11]. This approach is based on the likely reduction of environmental emissions linked to a reduction of fuel consumption when lightweight components are used. For example, Deng et al. reported the benefits of using flax fibres as reinforcement in polymer composites [12], Luz et al. proposed the use of sugarcane bagasse fibres as reinforcement in PP [13], Fogorasi et al. reported the potential of natural fibres for automotive sector [14], and Pietrini et al. proposed the use of totally degradable polymer composites when combining sugar cane bagasse with biodegradable polymer matrices such as poly-(3-hydroxybutyrate) [15].

The use of plant fibres as reinforcement in polymer composites is notably much more widespread, however, animal fibres have also shown to be effective reinforcements for polymers, and a viable choice for the development of new composites [16]. Accordingly, it is very common to find in the literature many environmental studies related to the use of wood, flax, jute, hemp, etc.... as reinforcement in composites formulations but few environmental studies referring to the use of fibres or residua from animals such as wool or chicken feathers fibres (CFs) [17]. In regard to CFs, they are made of hydrophobic keratin and is characterized by light weight, moderate biodegradability, high specific modulus and tensile strength [18]. Moreover, it is worth mentioning that, differently to some plant fibres, they are a true residue coming from the livestock industry. Hence, their application to the production of biocomposites is a worth exploring alternative of valorisation that could consume the huge number of CFs produced annually [19], moving towards a circular economy approach. In this sense, previous studies showed the feasibility of using CFs from slaughterhouse wastes as a filler or reinforcement in different polymeric matrix to perform alternative composites materials with different mechanical properties [20–24].

Anyhow, the overall sustainability of the aforementioned composites must be appraised and, up to now, Life Cycle Assessment (LCA) is the most commonly used approach for quantifying the environmental advantages or disadvantages occurring for activities, products and processes, by considering various impact categories [25]. Thus, the effort for assigning LCA studies of complex

products like cars and also aircrafts is quite high and it is possible to find in the literature many references dealing with the use of composite and bio-composites able to increase sustainability, provided that the technical constraints and requirements are fulfilled [26, 27]. Such publications do not only tackle the fabrication and the structural and mechanical characterization of new possibly useful materials but also analyze the environmental impacts over the whole life cycle of some products related to the automotive industry by using LCA [14, 28–31].

In the same direction, the present study aims to determine whether the use of a genuine biodegradable and biogenic waste such as CFs might involve some environmental credits compared to current composites used at the industry level. Such a goal is pursued by using a methodology that considers the constraints linked to mechanical properties that different materials must overcome so as to provide equivalent performances [32].

Concretely, two industrial applications for the new developed CFs-based composites were considered: a mobile application (i.e. automotive sector) and a stationary application. The latest is defined as one that, during the use phase, does not consume any kind of energy (neither fuel). For example, furniture, fences, construction panels or design objects can be considered as stationary applications.

The study focuses on the application of the Cradle-to-Grave LCA methodology as a tool to evaluate the environmental impact of composites made by blending PP and CFs and compare them with those of neat PP or PP reinforced with GF, materials traditionally applied in automotive sector as well as on stationary applications like appliance, furniture, terrace flooring, etc.

Materials and Methods:

The study follows up the four basic phases of the LCA methodology according to ISO 14040 [33] and ISO 14044 [34]: (1) goal and scope definition; (2) Life Cycle Inventory (LCI); (3) Life cycle impact assessment; and (4) interpretation. The four phases are presented in the following subsections.

To accomplish the LCI, two types of data were considered depending on their origins. Data obtained from processes carried out on a laboratory scale (i.e. Primary data) and data from the Ecoinvent v3 database (i.e. Background data). Detailed information about data and data quality is presented in section entitled Data and Data Quality, Primary and Background Data.

SimaPro 8.03 software, developed by Pré Consultants, was used as a tool to perform the LCA, following the CML-IA baseline 3.04 midpoint approach.

Goal and Scope

The main goal of this LCA study was to compare PP-CFs composites with conventional PP-GF ones, and also with analogue materials made of neat PP in a Cradle-to-Grave approach for their entire life cycle, including the following phases: extraction and processing of raw materials; manufacturing of the different materials considered, use, and End of life (EoL).

The assessment focuses on PP-CFs composites as it might be an alternative to PP or PP-GF composites for automotive and stationary industrial applications.

The flow diagrams and the assumptions of the study are explained in section entitled Systems Boundaries, Data Source and Assumptions.

Functional Unit

Given that the objective of the study is to compare different materials for a targeted industrial application, it is important to take into account that to obtain the same performance (i.e. the same stiffness than baseline material commonly used for the fabrication of the panels), the amount of material may be different in each case. Furthermore, the requirements would be surely different between mobile and stationary applications.

For this reason, the mechanical properties and the density of each material were considered to calculate the equivalent-mass, as recommended by Cooper[32]. Thus, Eq. 1 was used to estimate the mass of a functionally equivalent material, m_i , given the mass of a baseline material, m_b , knowing the Young's Moduli (E_i , E_b) and density (ρ_i , ρ_b) of both materials.

$$m_i = m_b \frac{\rho_i E_b^{1/3}}{\rho_b E_i^{1/3}} \quad (1)$$

For automotive applications, the chosen functional unit was the equivalent mass necessary to make all the internal panels of an average car (10 years lifetime, 150,000 km mileage) [15, 35]. In such scenario, the baseline material deemed was 20 kg of PP-GF since it is the amount that according to Pietrini et al. corresponds to the total weight of all internal panels of an average car with a composition of 63 wt% PP, 30 wt % GF and 7 wt% of maleated polypropylene (MAPP) [15].

For stationary applications, the chosen functional unit was the equivalent mass to manufacture flat non-structural

panels, taking 20 kg of PP-GF as the baseline material and 10 years as the lifetime of the panel.

Table 1 shows the composition, properties and equivalent mass considered to each material for both industrial applications. Note that the percentage of CFs is referred to the amount of clean, dry and crushed CFs since CFs are a waste that needs to be pre-treated as explained below in section entitled Systems Boundaries, Data Source and Assumptions.

The experimental density and the Young's Modulus of each composite were determined in a previous work [20] following the ASTM D792-13 for the density and ASTM D-638-14 for the Modulus [36, 37].

Systems Boundaries, Data Source and Assumptions

Three types of boundaries have to be distinguished: between the product system and the environment, between included and disregarded processes (cut-off) and between product systems (allocation). In this section, the three types of boundaries are detailed.

The systems boundaries between the product system and the environment for both industrial applications with composites made from PP-GF, PP-CFs and PP are shown in Fig. 1, Fig. 2 and Fig. 3 respectively.

For those applications developed that are based on PP-CFs composites, notice that CFs need to be cleaned, dried and crushed before blending with polymeric matrix (PP and MAPP) since CFs are true wastes coming from a slaughterhouse and are impregnated with other organic wastes, such

Table 1 Material composition, properties and equivalent mass

Material	Composition (wt %)				ρ (g/L)	E (MPa)	Equivalent mass (kg)
	CFs	GF	PP	MAPP			
PP-CFs	20	0	57	23	949.3	1362.9	21.9
PP-GF	0	30	63	7	1400.0	5750.0	20.0
PP	0	0	100	0	885.2	1063.8	22.2

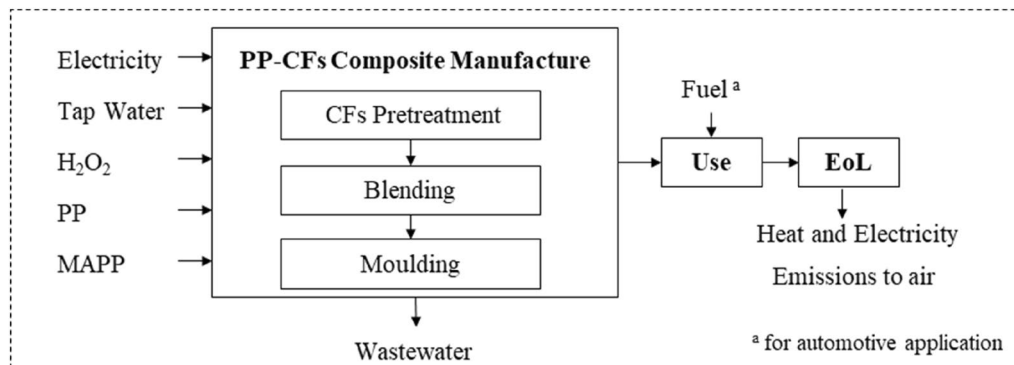


Fig. 1 Panels made from PP-CFs, system boundary

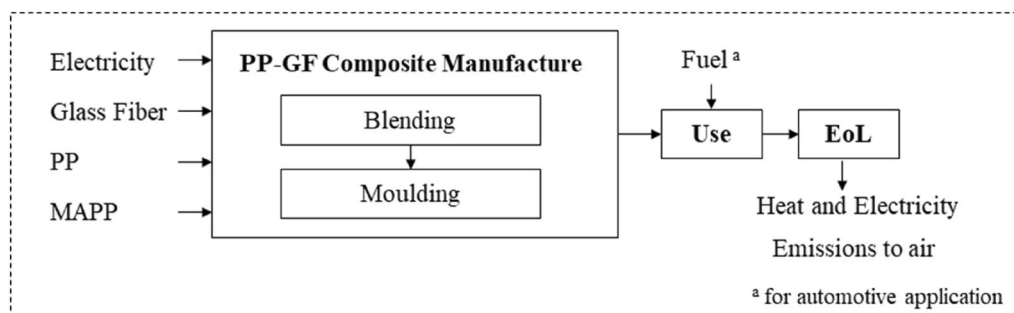
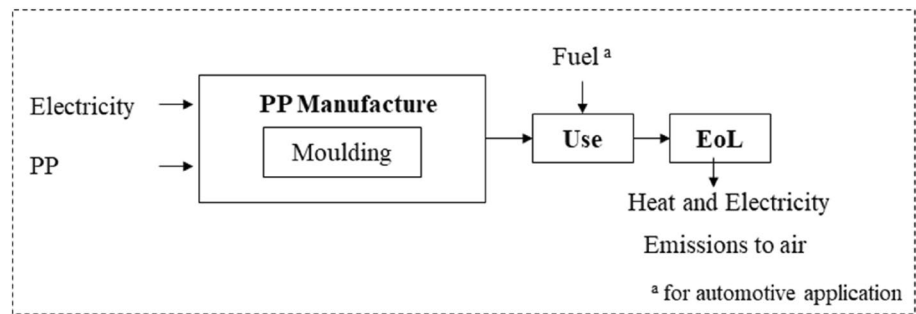


Fig. 2 Panels made from PP-GF, system boundary

Fig. 3 Panels made from PP, system boundary



as fat and blood, and potentially subjected to a rapid degradation. Experiments carried out in our laboratory showed that the use of hydrogen peroxide is the best solution to assure a complete sanitation of the CFs from the technical and environmental point of view. Besides, the efficiency of the aforementioned pre-treatment was proved by a microbiology test [20].

It is also worth to mention that to obtain composites with improved mechanical properties the use of MAPP was necessary to enhance the lack of compatibility between PP and CFs [20] or GF [15].

The allocation rules between the meat production and the feathers deserve a special mention. According to the Ministry of Agriculture and Fisheries, Food and Environment of the Spanish State, CFs wastes are animal by-products “with little or no commercial or economic value and without viable destination” [38]. For this reason, the authors assumed that there is no causal or economic relationship between the raising of poultry (non-functional flow) and the CFs (co-products). All the flows needed for fattening, as well as the chemicals used for the de-feathering are only imputable to the chicken meat [39]. Consequently, we have excluded those environmental impacts which are strictly attributed to chicken meat production.

The transportation of all the composite materials to the manufacturing facility is out of the scope of the study as it is indicated in the Goal and Scope section. Notice that the assembly of the panels, either in the case of the automotive application or the stationary application, was also left out of the studied systems since it equally impacts to all the systems considered and, consequently, the goal of the study is not affected by this cut-off.

For the automotive application, Fontaras et al. reported that the fuel consumption and car emissions depend on different factors: (a) factors related to vehicle characteristics and systems (such as vehicle mass, vehicle aerodynamics, tires and auxiliary systems); (b) factors related to the environmental and traffic conditions (such as weather, road morphology, traffic conditions); and (c) factors related to the vehicle driver (such as driving style and vehicle maintenance). From the list, the vehicle mass is one of the main factors influencing the fuel consumption of a vehicle under

low velocity driving conditions [40]. In this sense, Muñoz et al., expressed that fuel consumption has a direct relationship with vehicle weight and so it is the only aspect that could be allocated to this type of panel [11]. For this reason, the use of fuel is within the boundaries of the study but the emissions related to combustion in a car engine are not included. On the other hand, it is really complex to ascertain the exhaust emissions related to the combustion of an amount of petrol without taking into account many additional factors (not only the car weight) and, therefore making numerous assumptions dealing with traffic, engines, aerodynamics, etc. what would yield to different hypothetical, particular and non-representative scenarios used just for the sake of comparison. Thus, it was decided to consider that exhaust emissions are out of the boundaries of the system.

Regarding the EoL phase, incineration with energy recovery is the scenario for the final disposal of the different materials, disregarding the type of application. Even if incineration does not allow the recuperation of the materials, some authors found that incineration with energy recovery is a good alternative for composite materials [9, 12, 41]. Besides, Sommerhuber et al., reported for Wood-Plastic Composites (WPC) that a balanced market for demand and supply of secondary WPC is needed for an efficient recycling system, although it is currently not available today due to the small number of stakeholders and the low production of secondary WPC in Europe [42]. Therefore, it was considered that incineration with energy recovery is the most real scenario of EoL. In this regard, the amount of electricity recovered depends on the incinerated material (type and amount) and provides environmental credits equal to the impacts of the same amount of electricity if it was to be generated (See Table 4 for amount of electricity recovered). That means that for the generation of 1 kWh of electricity achieved by the incineration of a certain amount of material, the environmental load that would “normally” occur if such an amount of electricity would be generated is therefore subtracted.

Data and Data Quality. Primary and Background Data

Primary data used in this study were obtained from processes carried out in the laboratory. The scaling of data to

Table 2 Background LCI data sources

Input/process	Data source
Electricity: Electricity, low voltage (ES) market for/Alloc Def, U	Treyer et al. [44]
PP: Polypropylene, granulate (GLO) market for/Alloc Def, U	Ecoinvent [43]
MAPP:	
Maleic anhydride (RER) market for/Alloc Def, U	Althaus [45]
Polypropylene, granulate (GLO) market for/Alloc Def, U	Ecoinvent [43]
Glass Fibre (GF): Glass fibre (GLO)market for/Alloc Def,U	Ecoinvent [43]
Tap water: Tap water (Europe without Switzerland)/tap water production, conventional treatment/Alloc Def, U	Ecoinvent [43]
Hydrogen peroxide: Hydrogen peroxide, without water, in 50% solution state (GLO)/market for/Alloc Def, U	Ecoinvent [43]
Petrol, low-sulfur(RoW)/market for/Alloc Def, U	Ecoinvent [43]

Table 3 Elemental composition of CFs and Upper and lower heating value of CFs and PP [47, 48]

<i>Chicken feathers. Chemical composition</i>	
Oxygen (% wt without O from H ₂ O)	13.5
Hydrogen (% wt without O from H ₂ O)	8.6
Carbon (%wt. All biogenic)	61.5
Sulfur (%wt)	4.9
Nitrogen (%wt)	8.8
Chlorine (%wt)	2.6
<i>Chicken feathers UHV, LHV</i>	
Upper heating value (MJ/kg)	31.3
Lower heating value (MJ/kg)	29.3
<i>Polypropylene UHV, LHV</i>	
Upper heating value (MJ/kg)	36.16
Lower heating value (MJ/kg)	34.78

the industrial level is difficult because composites obtained from wastes are still in an incipient state of development in comparison with petroleum-derived plastics. Even so, some calculations and assumptions were made in order to have more realistic data, as explained in section entitled Life Cycle Inventory.

Background LCI data for the energy and material inputs come from Ecoinvent v3.3 data base [43]. Table 2 shows the Background data sources used to model the material and energy inputs.

Some other assumptions were also done:

MAPP consists of 1 wt% of maleic anhydride and 99 wt% of PP, according to the literature [46].

For automotive panels, the petrol consumption assigned to the panels was calculated following equation (Eq. 2) and the data published by Roes et al. [35] and Pietrini et al. [15]: i) the weight of the car without panels: 1222 kg (including 1.6 passengers); ii) the weight of PP-GF panels:

20 kg; and iii) fuel used during the life of car (150 000 km) with PP-GF panels: 9915.0 kg:

$$FC_{Panels,i} = 1 - \left(\frac{W_i}{W} \right)^{-0.7} FC_i \quad (2)$$

where $FC_{panels,i}$ is the fuel consumption assigned to panels (kg), W_i is the weight of the car with panels of type “i” (kg), W is the weight of the car without any panel (i.e. 1222 kg) and FC_i is the fuel consumption of the car with panels of type “i” during the entire lifetime of the car, calculated by using the following equation (Eq. 3) [15]:

$$FC_{New} = FC_{Conv} \left(\frac{W_{Conv}}{W_{New}} \right)^{-0.72} \quad (3)$$

where FC_{Conv} and W_{Conv} are respectively the fuel consumption and the weight of the car with the conventional panels (9915 kg and 1242 kg, respectively) and FC_{New} and W_{New} are respectively the fuel consumption and the weight of the car with the alternative PP-CFs proposed material.

For both industrial applications, the EoL, i.e., incineration with electricity recovery, was modeled based on the methodology documented by Doka G. The calculation tool for waste disposal for Ecoinvent LCI database v2.1 (2008) was used with corrections as October 2008 [47]. Table 3 shows the elemental composition and upper (UHV) and lower (LHV) heating value for CFs, necessary for the modeling, which were established using the Dulog’s formula [48].

Selected Impact Assessment Methods

SimaPro 8 software was used to perform the LCA, following the CML-IA baseline 3.04 midpoint approach, excluding infrastructure processes and long-term emissions. All the impact categories of the CML-IA baseline 3.04 midpoint approach were selected to assess the LCA.

Table 4 Life cycle inventory for panels

PP-CFs panels (equivalent mass 21.9 kg)			PP-GF panels (equivalent mass 20.0 kg)			PP panels (equivalent mass 22.2 kg)		
Input	Unit	Amount	Input	Unit	Amount	Input	Unit	Amount
<i>PP-CFs composite manufacture</i>								
<i>CFs pretreatment</i>								
Tap water (Cleaning)	L	357.9						
Hydrogen peroxide (Cleaning)	kg	1.2						
Electricity (Cleaning)	kJ	1841.7						
Electricity (Drying)	kJ	64,482						
Electricity (Crushing)	kJ	8672.4						
<i>PP-CFs composite manufacture</i>			<i>PP-GF composite manufacture</i>			<i>PP composite manufacture</i>		
<i>Blending</i>			<i>Blending</i>			<i>Blending</i>		
Electricity (Blending)	kJ	93,324.7	Electricity (Blending)	kJ	85,228.0			
PP	kg	13.9	PP	kg	13.9			
MAPP	kg	5.6	MAPP	kg	1.54			
Pre-treated CFs	kg	4.8	GF	kg	6.6			
<i>PP-CFs composite manufacture</i>			<i>PP-GF composite manufacture</i>			<i>PP composite manufacture</i>		
<i>Moulding</i>			<i>Moulding</i>			<i>Moulding</i>		
Electricity (Moulding)	kJ	158,161.8	Electricity (Moulding)	kJ	144,440.0	Electricity (Moulding)	kJ	159,551.4
						PP	kg	22.2
<i>Use</i>								
Fuel consumption assigned to panels. ¹ (FC _{panels,i}) (kg)	kg	126.1	Fuel consumption assigned to panels. ¹ (FC _{panels,i}) (kg)	kg	115.2	Fuel consumption assigned to panels. ¹ (FC _{panels,i}) (kg)	kg	127.8
<i>EoL</i>								
Electricity (recovery)	MJ	79.9	Electricity (recovery)	MJ	49.2	Electricity (recovery)	MJ	54.61

^aOnly for automotive application calculated from Eq. 2

Results and Discussion

Life Cycle Inventory

Table 4 shows the life cycle inventory flows for the three panels considered and for both industrial applications. All the data are referenced to the equivalent mass calculated in section entitled Functional Unit.

The amount of tap water and hydrogen peroxide necessary for the CFs sanitizing pre-treatment process were determined by experiments carry out on laboratory scale. The CFs cleaning process was done in a conventional washing machine with 5 kg capacity working 102 min at 35 °C. The electricity consumed was measured using a potentiometer (12Wh/kg_{in}).

The energy requirements for drying were estimated considering that drying was present in two steps of the process:

i) firstly, after the cleaning pretreatment in order to safely store the CFs and ii) secondly, before blending and moulding to avoid the presence of water during the operation. Calculations were conducted taking into account the enthalpy balance represented by Eq. 4:

$$Q = m_{dryCF} * (h_{CF,out} - h_{CF,in}) + \sum m_{dryair} * (h_{air,out} - h_{air,in}) \tag{4}$$

$$h_{CF} = (C_{CF} + XC_{water})T \tag{5}$$

$$h_{air} = (C_{air} + YC_{steam})T + Y\Delta H_v \tag{6}$$

where: $m_{dry i}$ = mass of dried i material (CFs or air) (kg), $h_{i,j}$ = enthalpy of i (CFs or air) at j (inlet or outlet) (kJ/kg K), C_i : specific heat of i (CFs, air, water or steam) (kJ/kg K), X : water content of CFs (kg water/kg dry CFs), Y : humidity

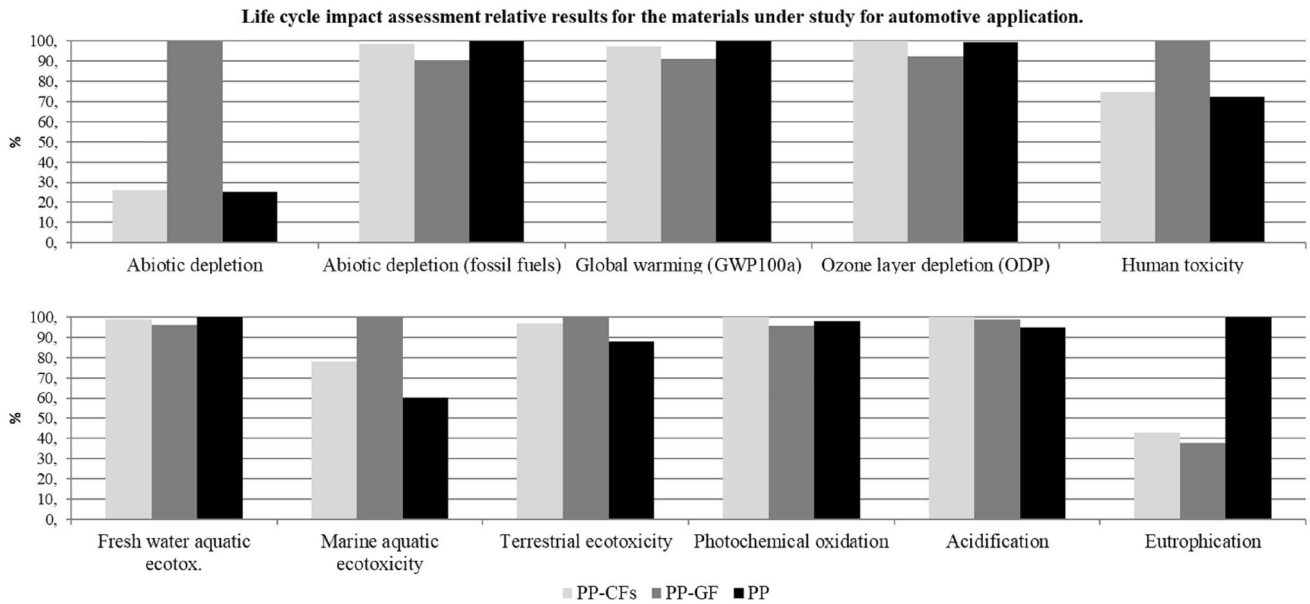


Fig. 4 Life cycle impact assessment relative results for the materials under study for automotive application

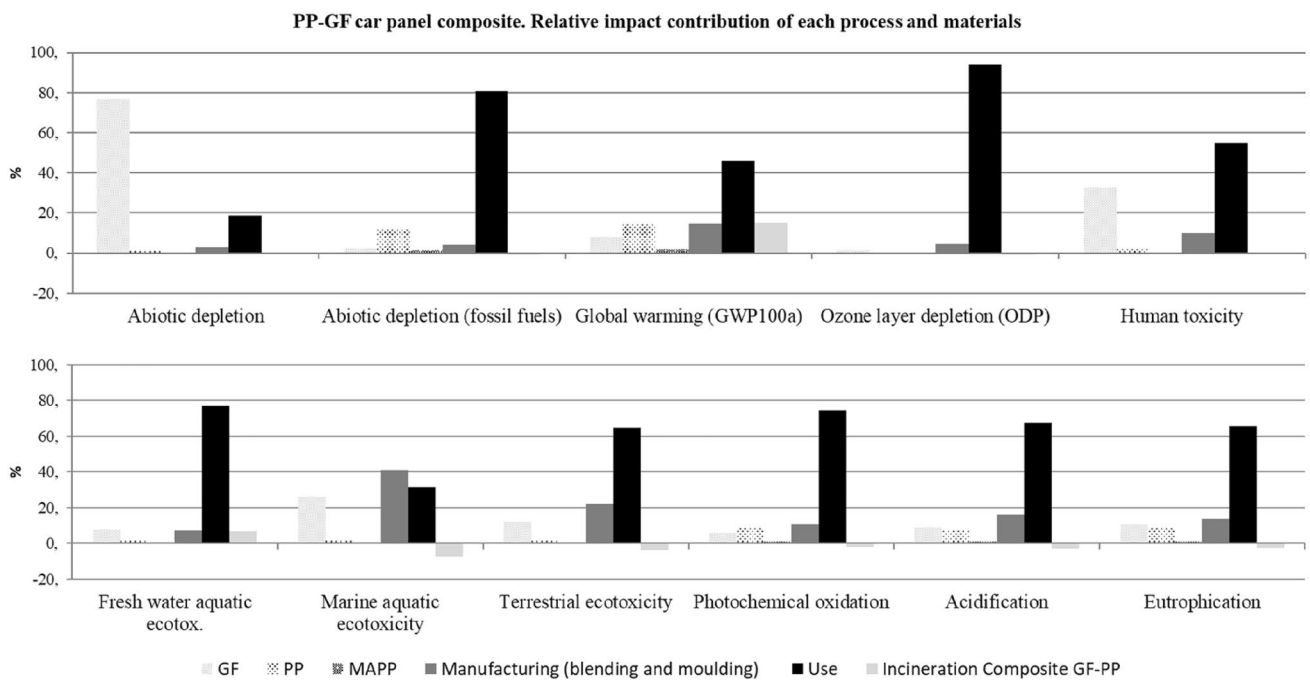


Fig. 5 PP-GF car panel composite. Relative impact contribution of each process and materials

ratio (kg water/kg dry air), T : temperature (K), and ΔH_v : latent heat of water (kJ/kg).

The electricity consumption for crushing process was calculated using the device power and time ($100\text{Wh}/\text{kg}_{\text{out}}$).

The contaminant load of wastewater from cleaning CFs was measured and counted as an output. ($61.1\text{ gCOD}/\text{kg}$,

$15.9\text{ g BOD}_5/\text{kg}$, $33.9\text{ g suspended solid}/\text{kg}$ and $1.3\text{ g oils}/\text{kg}$. All the data was referred to 1 kg of clean CFs).

Life Cycle Assessment. Automotive application

As showed in Fig. 4, the PP-GF composite presents low environmental impacts in all categories considered except

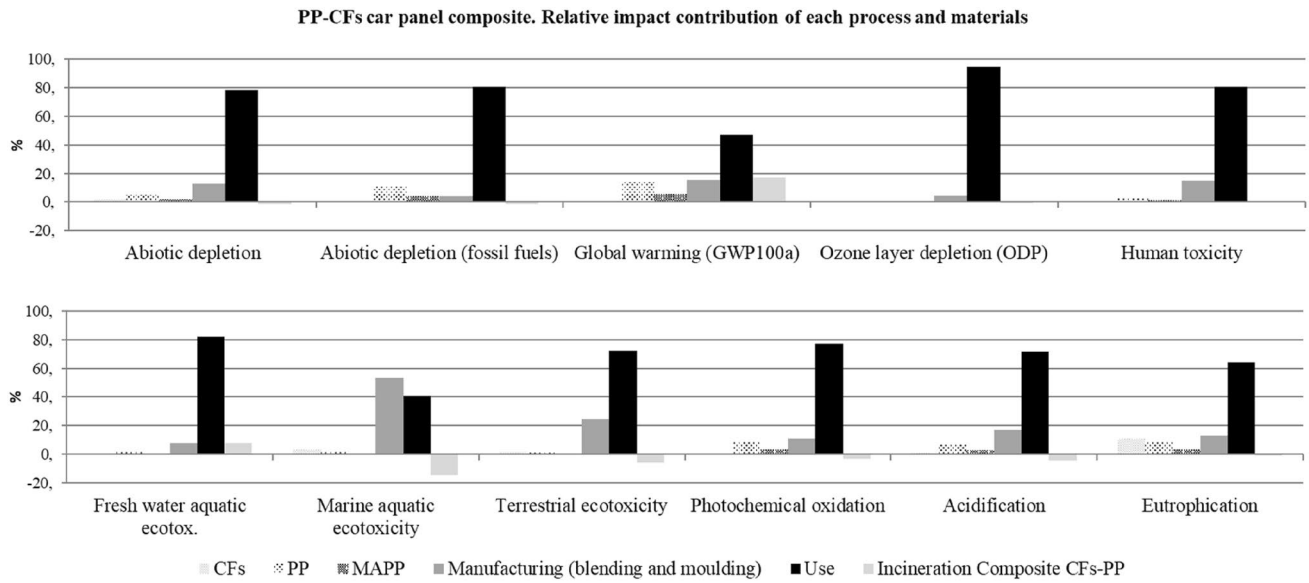


Fig. 6 PP-CFs car panel composite. Relative impact contribution of each process and materials

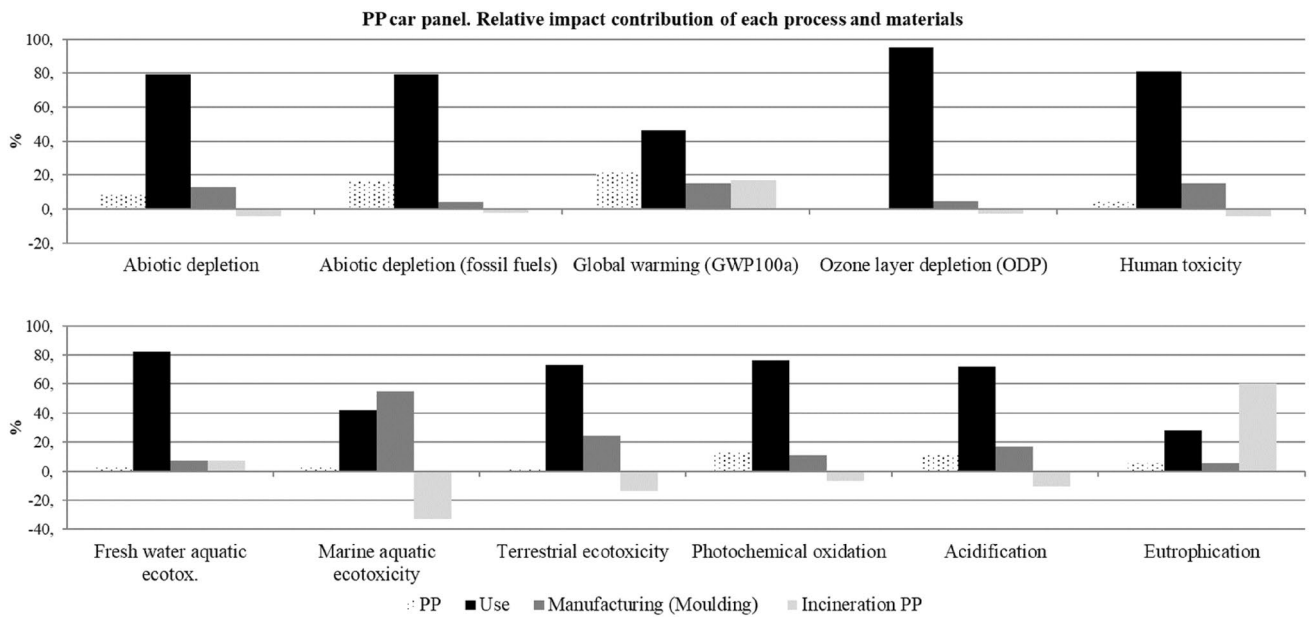


Fig. 7 PP car panel. Relative impact contribution of each process and materials

for: abiotic depletion, mainly due to the GF production (see Fig. 5); Human toxicity, mainly due to fuel consumption during the use phase (see Fig. 5); and Marine aquatic and terrestrial ecotoxicity, due to Manufacturing and fuel consumption (see Fig. 5).

Although the density of PP-CFs composite and PP are lower than the PP-GF ones, the lower Young’s Modulus cause a higher equivalent-mass needed to have the same mechanical performance (see section entitled Functional Unit and Table 1). This fact is of particular importance since

the weight mainly affects the use phase of mobile applications, the one that presents the greatest contribution to all the environmental categories impact as it is showed in Figs. 5, 6 and 7. Thus, there are greater environmental impact for PP-CFs and PP car panels in comparison with PP-GF ones.

As it was mentioned above, Fig. 5, 6 and 7 show the relative impact contribution of each process and materials required to perform each car panel considered (PP-GF, PP-CFs and PP, respectively) in the categories analysed. From the results, it can be seen that for all the materials

studied, the use phase is the one that has the greater contribution to most of the impact categories considered. It is worthwhile to mention that for PP-GF car panels the GF production is the phase that contribute the most to the consumption of abiotic resources mainly due to the inorganic raw materials needed for their manufacture. Besides, for all the car panels the manufacture phase has an important contribution to marine aquatic toxicity, principally due to the electricity consumption in this phase and the necessary hard coal to produce it.

Other studies, related to carbon fibre reinforced polymers applied to replace structural car components, reveal that the use phase is the most contributing step in the whole life cycle of a part, highlighting the major effect of lightweight design on the environmental burdens [49]. Also, Pietrini et al. [15] showed that the definition of the use phase, whether stationary or mobile, is crucial as it influences the overall environmental footprint.

A deep assess of this fact let us to conclude that the new material developed using CFs will be more appropriate for stationary applications where the use phase does not have a significant influence (see section entitled Life Cycle Assessment. Stationary Application).

Note that the negative values observed in Figs. 5, 6 and 7 indicate the percentage of impact avoided due to electricity recovery during the incineration process. In all the impact categories with a negative bar the emissions avoided by the recovery of electricity are greater than the emissions due to incineration itself.

Life Cycle Assessment. Stationary Application

In order to demonstrate the efficiency of the new PP-CFs composite in stationary application, the LCA of this material was examined and the results are showed in Fig. 8 where a better environmental performance for the PP-CFs in comparison with PP-GF in all environmental categories is observed, except for; Abiotic depletion (fossil fuels), Global warming potential and Eutrophication for which there are no significative differences.

In addition, PP presents a better environmental impact in some categories than PP-CFs (i.e. Abiotic depletion, Ozone layer depletion, Human toxicity, Marine aquatic toxicity, Terrestrial ecotoxicity and Acidification).

Figures 9, 10 and 11 show the relative impact contribution of each process and each material required to perform PP-GF, PP-CFs and PP for stationary application. It can be concluded that for both composite materials the manufacturing step has a significant contribution mainly in Ozone layer depletion, Human toxicity, Marine aquatic toxicity and Terrestrial ecotoxicity due to the electricity consumption in the manufacturing phase.

Moreover, the contribution of GF is significant in the PP-GF whereas the environmental impact of the CFs is not so significant in PP-CFs except for Eutrophication that is comparable to PP-GF although for different reasons. In the case of PP-CFs material, its contribution to eutrophication is mainly due to the wastewater generated in the CFs pretreatment and the electricity consumed for

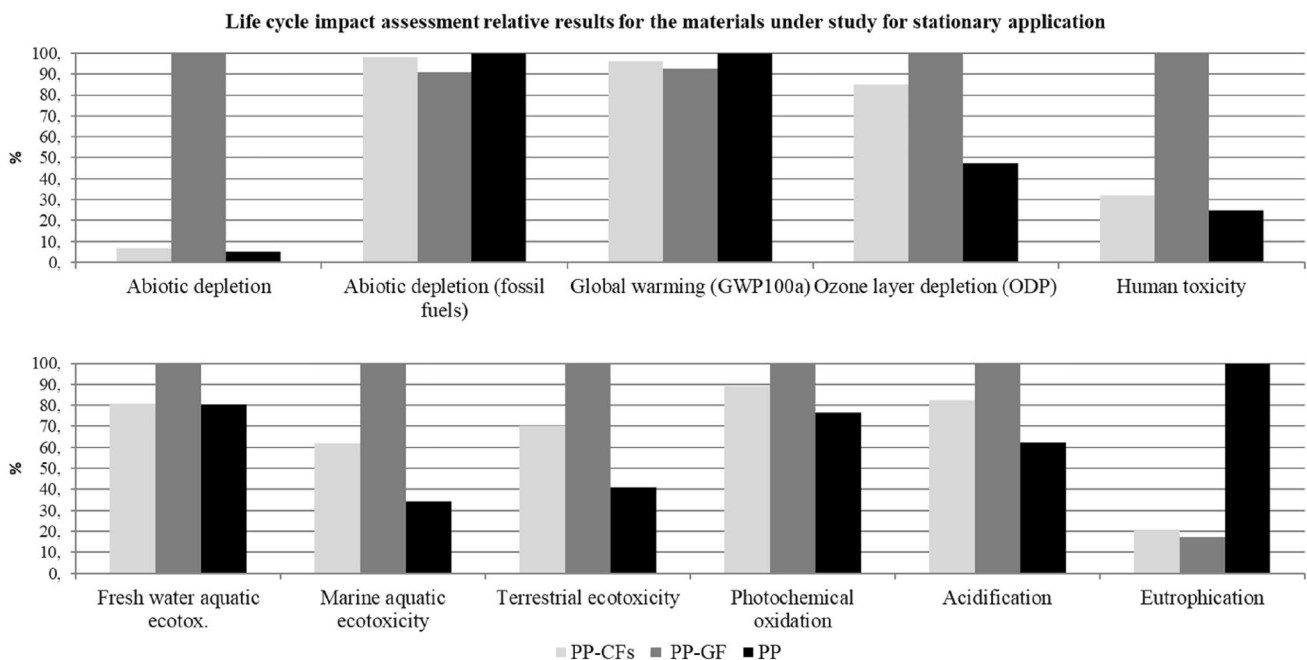


Fig. 8 Life cycle impact assessment relative results for the materials under study for stationary application

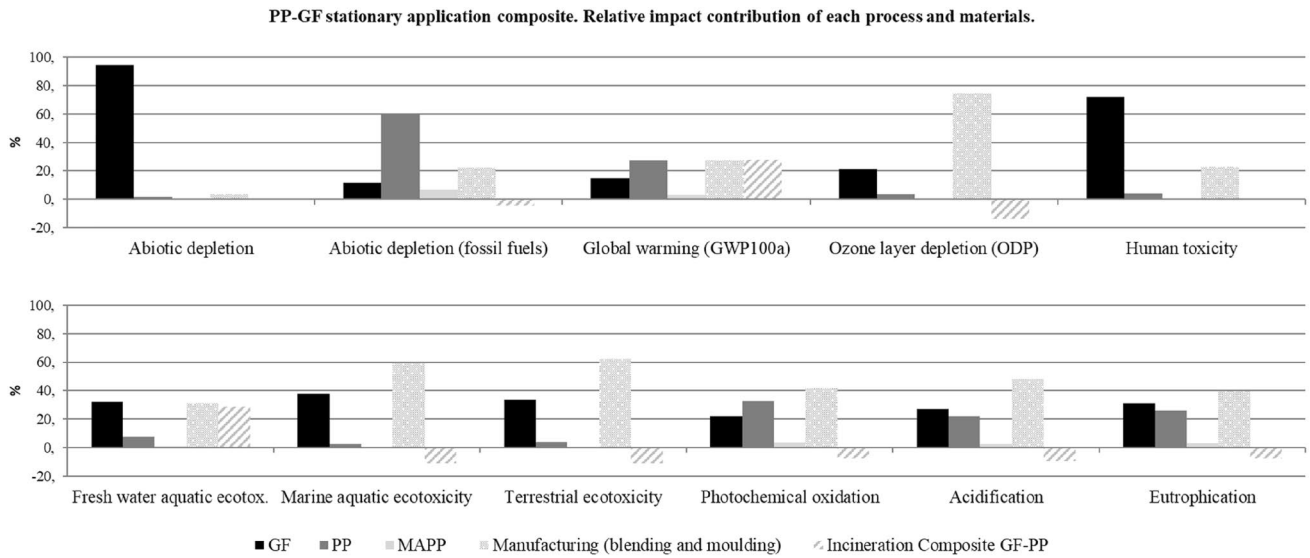


Fig. 9 PP-GF stationary application composite. Relative impact contribution of each process and materials

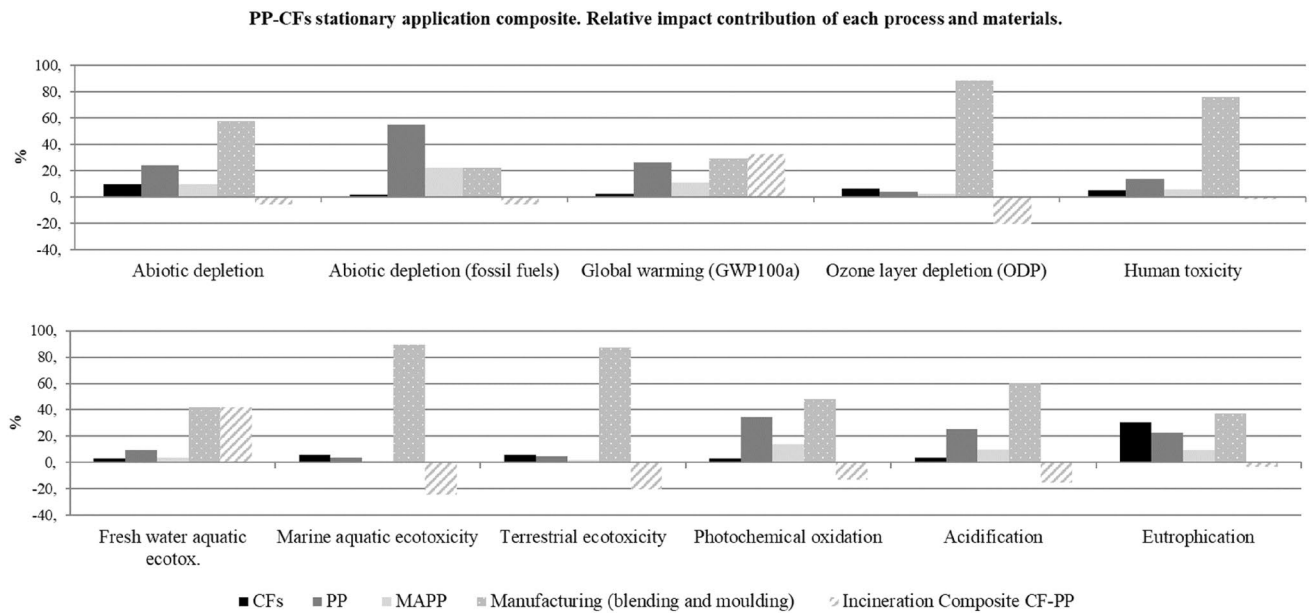


Fig. 10 PP-CFs stationary application composite. Relative impact contribution of each process and materials

manufacture whereas for PP-GF the contribution is due to the wastewater generated in the glass fibre production and to the consumption of electricity for manufacture also. The previously mentioned better environmental performance of PP in some impact categories could be explained because the incineration of PP material provides some extra environmental credits in comparison to PP-CFs composite since PP has a higher upper and lower heating value than PP-CFs resulting in a greater electricity recovery.

Conclusions

This work pointed out the importance of using the equivalent mass concept when materials of different mechanical properties are to be compared under an environmental point of view, because results are sometimes counter-intuitive. For instance, in the studied case although the density of PP-CFs composite and PP material are lower than that of PP-GF, the lower Young's Moduli of PP-CFs

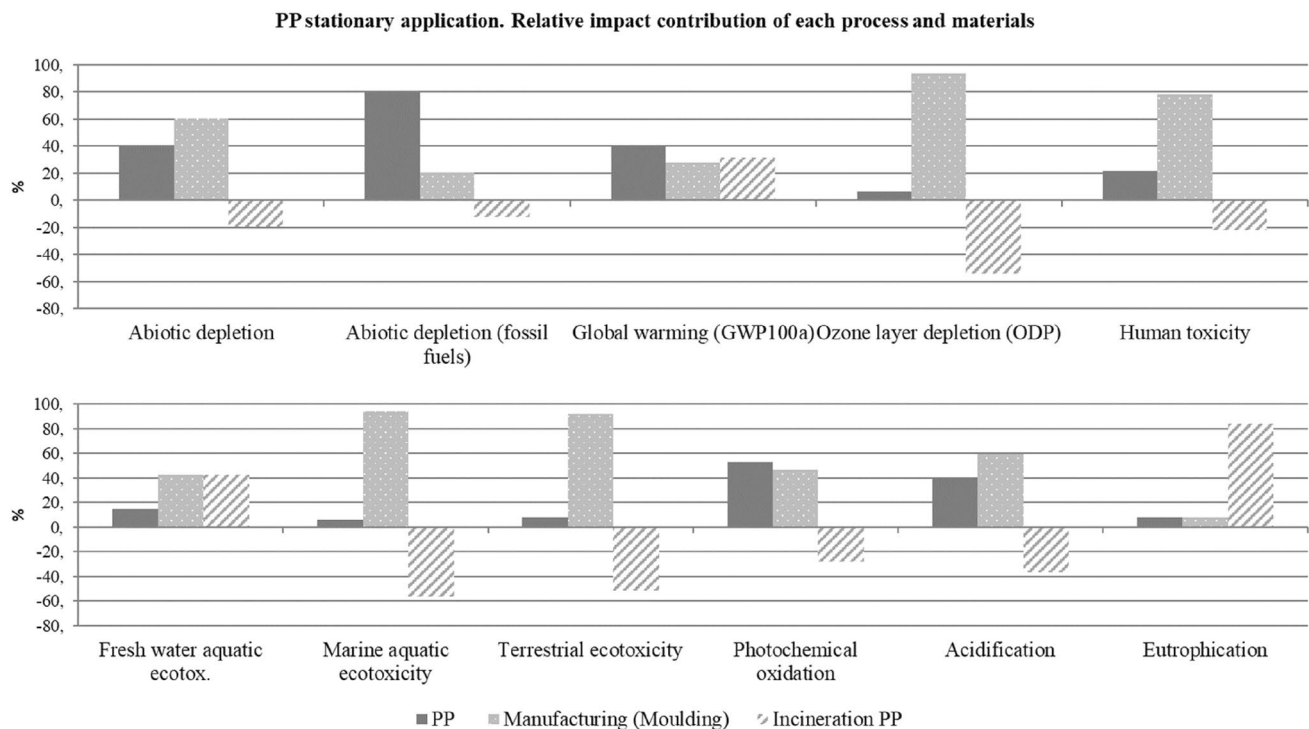


Fig. 11 PP stationary application. Relative impact contribution of each process and materials

and PP provoke that a greater equivalent mass is required to achieve comparable mechanical performance (i.e. stiffness).

Consequently, due to the increase of the prime material used, it was observed that when the new CFs based composite are used some environmental impacts are higher than those of the PP-GF counterpart, such as Abiotic depletion (fossil fuels) or Global warming. Such situation happens independently of the type of application.

However, some of the environmental impacts are highly influenced by the type of application. For instance, the Ozone layer depletion of composites containing CFs is lower for that of PP-GF just for the stationary application, whereas is higher for the automotive application. In fact, for automotive applications, some environmental impacts are usually higher for most categories compared to PP-GF composites mainly due to the higher consumption of fuel during the use phase, related to the weight increase.

Thus, the use of biogenic wastes such as CFs to fabricate composites has demonstrated to be an efficient alternative to conventional materials preferably for stationary applications and not so for uses that involve motion or transport. That said, it is crucial to understand that such composites profit from a waste and reduce the consumption of prime materials, what should also be considered from a sustainable point of view.

Nowadays, several proposals of stationary items (i.e. urban furniture, acoustic isolation panels or non-structural panels) made of waste-based biocomposites are under study and the research shown in this work contributes to the general scientific background that may accelerate their acceptance.

Anyhow, the feasibility and the selection among the potential industrial applications would require more accurate data regarding the lifetime of the new developed materials so ageing testing is suggested as future work.

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Data Availability All data generated or analysed during this study are included in this published article.

Declarations

Competing interests The authors declare that they have no competing interests.

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