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Ecodesign of automotive components making use of natural jute fiber composites

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ABSTRACT

Nowadays, the world faces unprecedented challenges in social, environmental and economical dimensions, in which the industrial design has showed an important contribution with solutions that provide positive answers regarding these problems. In particular, due to its relevance, the automotive industry confronts a moment of crises, and based on the ecodesign of products it has been transforming the challenges in opportunities. In this context, the use of natural fiber composites, produced in developing countries, have presented several social, environmental and economical advantages to design "green" automotive components. Thus, this work through LCA method demonstrates the possibility to use natural fibers through a case study design which investigates the environmental improvements related to the replacement of glass fibers for natural jute fibers, to produce a structural frontal bonnet of an off-road vehicle (Buggy). Results pointed out the advantages of applying jute fiber composites in Buggy enclosures.

1. Introduction

Environmental and economical concerns are stimulating research in the design of new materials for construction, furniture, packaging and automotive industries. Particularly attractive are the new materials in which a good part is based on natural renewable resources, preventing further stresses on the environment. Nevertheless is important to know that renewable resources depend of a balance, in which their harvests have to be lower than its growth, in this sense jute fibers need to be used based on a sustainable system to avoid the Amazon deforestation. Examples of such raw material sources are annual growth native crops/plants/fibers, which are abundantly available in tropical regions over the world. These plants/fibers (like jute and sisal) have been used for hundreds of years for many applications such as ropes, beds, bags, etc. If new uses of fast growing, native plants can be developed for high value, non-timber based materials, there is a tremendous potential of creating jobs in the rural sector. These renewable, non-timber based materials could reduce the use of traditional materials such as wood, minerals and plastics for some applications [1].

Renewable fibers are often considered only for markets that require low costs and high production rates and can accept low performance. However, these fibers have many properties that would be an advantage in other markets, such as light non-abrasive and low energy requirements for processing. Their potential for use in molded articles not needing high strength for acceptable performance has been tried in equipment housings, roofing for low-cost housing, and in large diameter piping [2]. Moreover, automotive and packaging industries are demanding a shift of their design from oil-derived polymers and mineral reinforcement materials to natural materials focusing the recyclability or biodegradability of "green" products at the end of life.

1.1. Vegetable fibers

The wild use of glass fibers causes several environmental impacts mainly due to its disposal phase related to the landfill or even incineration without the necessary gas emission control. Their characteristics of strong material contributes to increase the problem regard to the narrow capacity of the environment to absorb industrial waste. In this context, researchers such as Puglia [3], Suddell [4] and Yuan [5] have already been studying natural fibers as replacement of glass fibers, improving the environmental performance of materials and products. Natural fibers can be

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Table 1
Mechanical properties of fibers. (Source: Mohanty [8] and Alves [9]).

Fiber	Density (g/cm^3)	Elastic modulus (GPa)	Specific elastic modulus (E/ρ)	Tensile strength (GPa)	Specific tensile strength (σ/ρ)	Elongation at break (%)
E-Glass	2.6	73	28.07	1.8–2.7	0.69–1.04	2.5
Carbon (PAN)	1.8	260	144.44	3.5–5.0	1.94–2.78	1.4–1.8
Aramid	1.45	130	89.66	2.7–4.5	1.86–3.10	3.3–3.7
Jute	1.45	10–32	6.89–22.07	0.45–0.55	0.31–0.38	1.1–1.5
Sisal	1.45	26–32	17.93–22.07	0.58–0.61	0.40–0.42	3–7
Coir	1.33	4–6	3.01–4.511	0.14–0.15	0.11	15–40

PAN – Polyacrylonitrile.

classified according to their source: vegetable, animal or mineral, and are usually used as reinforcement of thermoplastic and thermosetting polymeric matrices. According to Eichhorn [6], vegetable fibers are the most commercially important fibers with potential to use in composite materials, which jute fibers (Corchorus capsularis) have a high world annual production at about 2300 (10^3 ton.).

Vegetable fibers offer several advantages in comparison with synthetic fibers. They are biodegradable (crucial at the end of life of products), non-abrasive to processing equipment, are CO2 neutral and can be used as acoustic and thermal insulators [7]. Furthermore, they are an important source of income for agricultural societies. Still they are light weight and have high specific strength when compared to glass fibers. Table 1 shows the properties of some natural and conventional synthetic fibers.

Other great advantages of the vegetable fibers are their low cost and the positive social impact. They are native plants of many countries and have been in use for decades in the textile and paper industries. In Brazil one can find many kinds of fibers such as sisal, jute, coir and curauá, all of them already with commercial applications. Brazil has potential to produce about 10,000 ton/year of vegetable fibers that can be found natively or cultivated, becoming a source of income for several local communities [10]. Marsh [11] made an interesting qualitative comparison between natural and glass fibers pointing out the advantages in use natural fibers.

1.2. Automobile and jute fiber

Nowadays, plenty of examples can be found of the use of vegetable fibers as reinforcement of thermoplastic and thermosetting polymers such as polypropylene, polyethylene, polyester and epoxy to produce what may be called “friendly” composites [12,13]. In the last decade natural fibers have raised interest with regard to their use as reinforcement within composite materials to replace glass fibers. The automotive industry is one of the most avid users of natural composite materials in their products in interior applications such as door panels and trunk liners [4]. According to DEFRA’s report [14] it is expected an increase of the use of natural fibers in automotive components at about 54% per year, since European and American car makers have been already using them to achieve Environmental Directives. In USA automotive companies are embracing natural materials: about 1.5 million of vehicles are already using vegetable fibers such as jute, hemp, kenaf as reinforcement of thermoplastic and thermosetting polymers [15].

In Brazil some automotive initiatives are concerned with the selection of “greener” materials from renewable sources. For instance, in 1992 Mercedes-Benz of Brazil agreed to make an initial investment of US$1.4 million to research about the use of natural fibers in its products. Nowadays it has a partnership with Federal University of Pará to manage the project POEMA (Poverty and Environment in Amazonia). This initiative translates into new jobs in the coconut fiber production including agricultural producers, and processing plant workers [16]. In fact automotive textiles are the growing markets in terms of quantity, quality and product variety [17]. The European and North American market for vegetable composites reached 685,000 tones, valued at 775 million US dollar in 2002 [18]. European regulations play an important role as a driving force toward the sustainable mobility. For instance, the directive related to the end of life vehicles, predetermines the deposition fraction of a vehicle to 15% in 2005, and then gradually reduced to 5% in 2015 [19]. In this sense, panels and others

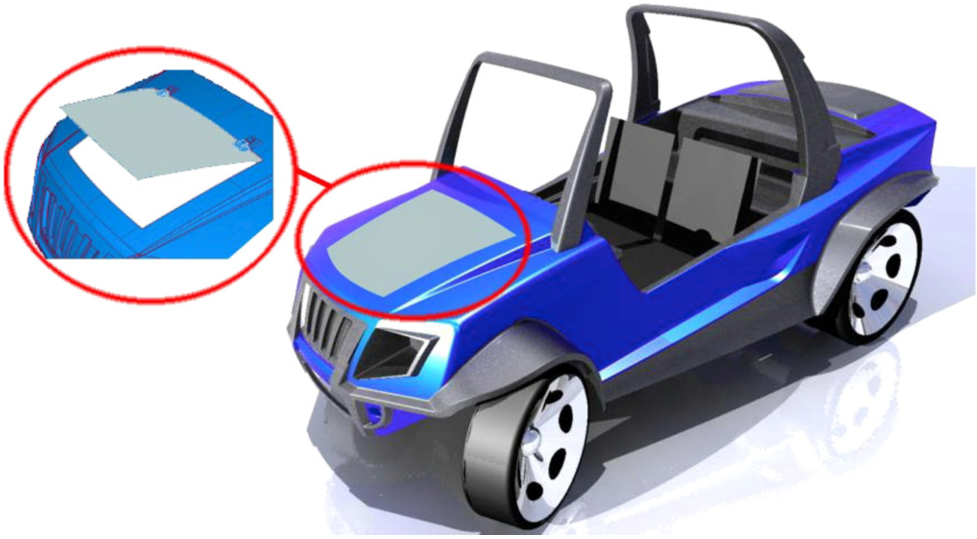

Fig. 1. Frontal bonnet of the buggy (FU).

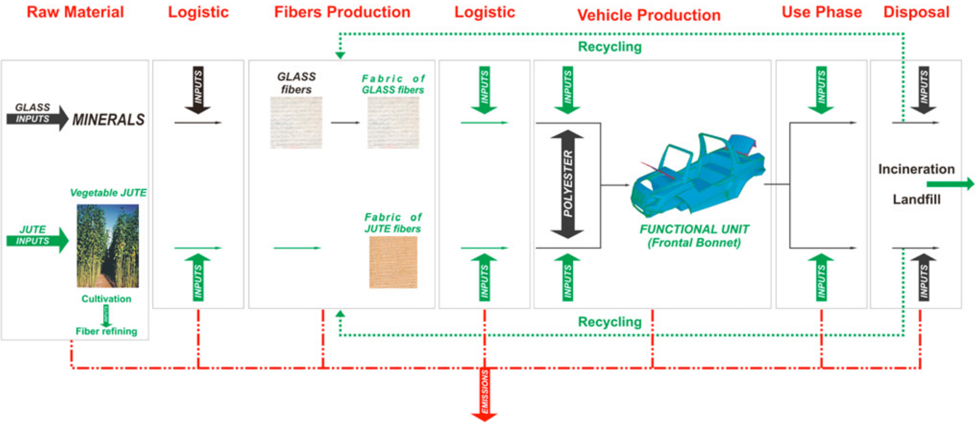

Fig. 2. Boundaries of the LCA.

automotive components made from jute fibers or other bio-thermoplastic and hybrid composites are already in use [20–23].

Jute is one of the most well-known vegetable fibers, mostly grown in countries such as India, Bangladesh, China, Nepal and Thailand. Together they produce about 95% of the global production of jute fibers [24]. In this context, the use of the jute fibers may find areas of applications in automotive components. As a vegetable reinforcement of material composites jute fibers have many advantages as said before. Some might consider part of those properties as disadvantages, such as biodegradable and combustible, but those features provide a means of predictable and programmable disposal not easily achieved with other resources [25]. Most researches concentrate on jute fiber/non degradable polymer composites, so research about jute/biodegradable polymer composites are limited [26]. Similarly to synthetic fiber composites, the mechanical properties of the final product made of jute fibers also depend on the individual properties of the matrix, fiber and the nature of the interface between them.

1.3. *Objectives of the study*

The goal of this study is to assess the environmental impact of using jute fiber composites and their necessary technical treatments for automotive design applications to manufacture the enclosures of a buggy vehicle. Thus, compare them with the impacts raised by current enclosures made of glass fiber reinforced plastic (GFRP) composites over the entire life cycle of the buggy. The study and project of the buggy is being developed in partnership with a traditional Brazilian company (ANCEL-REINFORCED PLASTICS), which employs 150 people and produces technical parts made of GFRP with a volume production of about 100 ton per month. The study intends to assess the consequences of replacing the current reinforcement material for untreated and treated jute fibers on the overall sustainability of this specific and important automobile sector in Brazil (entertainment).

The choice of this buggy case study contributes with the particular automotive sector which has a relevant social value for local communities as source of income for mobility due to the increase of the tourism in Brazil [27]. The players in this Brazilian business are all SME's or micro companies that produce at most several dozens of cars per year. In this context, a change in materials employed is not very demanding in terms of capital investment, as long as the manufacturing and assembly sequences are not significantly altered, and this automobile sector is particularly adequate to experiment with different options in real products. This is an especially adequate proving ground for environmentally conscious manufacturing, since no major investments have to be done to achieve a final product that can afterwards be assessed and compared with more traditional products. According to the Ancel, the selling of the buggies in Brazil is estimated about 2500–3000 vehicles/year.

Table 2
Damage and impact categories. (Source: EI-99 [37]).

Damage category	Impact category	Unit
Human Health	Carcinogens	DALY
	Respiratory organics	
	Respiratory inorganics	
	Climate change	
	Radiation	
	Ozone layer	
Ecosystem Quality	Ecotoxicity	$PDF^{*}m^{2*}year$
	Acidification/Eutrophication	
	Land use	
Resources	Minerals	MJ surplus
	Fossil fuels	

2. Case study: product life-cycle

To achieve the environmental goals of this project, a Life Cycle Assessment (LCA) was performed. LCA is a method which intends to

Table 3
Phases of the jute (plant – fibers).

Plant phase	Characterization
Cultivation	Manual No chemical substances
Harvest	Manual Annual
Productivity	1500 kg/ha
Decorticate Phase	
Maceration	Manual in Amazon River Placed next to harvest, no transports
Fibers productivity	5% of the plant
Wastes	50% used in pen of cattle 50% undergoes natural decomposition in Amazon River
Fabric's Production Phase	
Transports (300 km)	Trucks – 12 tons; Coasters – 25 tons
Carding-machine	About 4 tons, made mainly of steel Energy consumption – 3.1 kWh Disposal – about 50 years
Productivity	1000 kg/42 h
Suspended particles	About 0.3 kg/1000 kg of fabric

Table 4
Inputs of the bonnets production.

Bonnet	Injection flow (cc/min)	Volume of the fiber (%)	Mass of the bonnet (kg)	Mass of the fiber (kg)	Injection time (seg)	Total energy consumption (kW.h)
Jute Fibers (untreated and treated)	45	31	1.77	0.65	353	18.5
Glass Fibers	50	21	2.02	0.74	364	17.9

evaluate the environmental impacts and damage caused by a product over its entire life-cycle. It can be used to promote improvements in products or processes [28] from raw materials extractions to the disposal in an interactive process of data that can be obtained by sustainable design procedure. This approach is called the "cradle-to-grave" and has advantages in revealing potential, but not always evident environmental impacts [29]. Other issues of this study are discussed in the concluding part of the paper.

2.1. Bonnet as functional unit (FU)

In this study, the frontal bonnet of the buggy was assigned as functional unit (Fig. 1) or in other words, the functional unit could be stated as "the engine cover of 0.35 m^2 which achieves the required mechanical and structural performance". The choice of the bonnets was due to the real production of them, hence obtaining their real inputs. As an experimental and pragmatic study with the Brazilian company, three different jute bonnets and one glass bonnet were produced each one with six layers of bi-axial jute fibers or glass fibers, respectively, with the following stacking sequence [(0/90), (45/−45), (0/90)]. Despite the higher mechanical strength of the glass bonnet, this stacking sequence used to produce the all bonnets achieved a useful mechanical behavior of both the jute and glass bonnets. They were produced using a RTM UNIT obtained from ISOJET Equipments. Unsaturated Polyester resin obtained from Matexplas Ltda. (Lisbon, Portugal) was used as the matrix resin. Methyl Ethyl Ketone Peroxide (PMEK) also obtained from Matexplas was used as the curing agent. Jute fibers were supplied by Castanhal Têxtil Inc. [30] from Amazonas State, Brazil and glass fibers were also supplied by Matexplas Ltda. (Lisbon, Portugal). The equivalence between the two bonnets in terms of strength and stiffness was already established elsewhere [31,32], where two treatments were performed in jute fibers to improve the mechanical behaviors of the jute composites, then to ensure the achievement of the technical project requirements.

2.2. Boundary conditions (BC)

The LCA was performed to find environmental impacts related to the composite materials used to produce the frontal bonnet of the buggy. Thus its BC is the entire life cycle of the bonnets made of composite materials and their influence for whole vehicle, from the extraction of raw materials, over production processes and the use phase to the end of life of the buggy. The BC includes all of needed transports as well as the infrastructure to apply the treatments at jute fibers and to produce the bonnets even to dispose them.

The inputs regarding to the jute fibers cultivation and production were provided by supplier, nevertheless it also can be found in the literature. Inputs related to the polyester matrix, glass fibers and vehicles used to mobility were based on SimaPro 7.0 [33] database in its IDEMAT and Ecoinvent libraries. Inputs related to the treatments of the jute fibers and the productions of all bonnets were based on Table 4 and ANCEL Inc. database. The journey logistic inputs were based on the supplier's database, while electric energy inputs were obtained from Coltro [34] and they are related to the Brazilian electric energy system. Finally, the landfill and incineration scenarios of the end of life of the bonnets were based on Brazilian government reports [35,36], the recycling scenario was based on experimental results. Fig. 2 shows the schematic diagram of the assumed life-cycle to the functional unit, in which green color inputs were obtained by authors and black color inputs were obtained in SimaPro database.

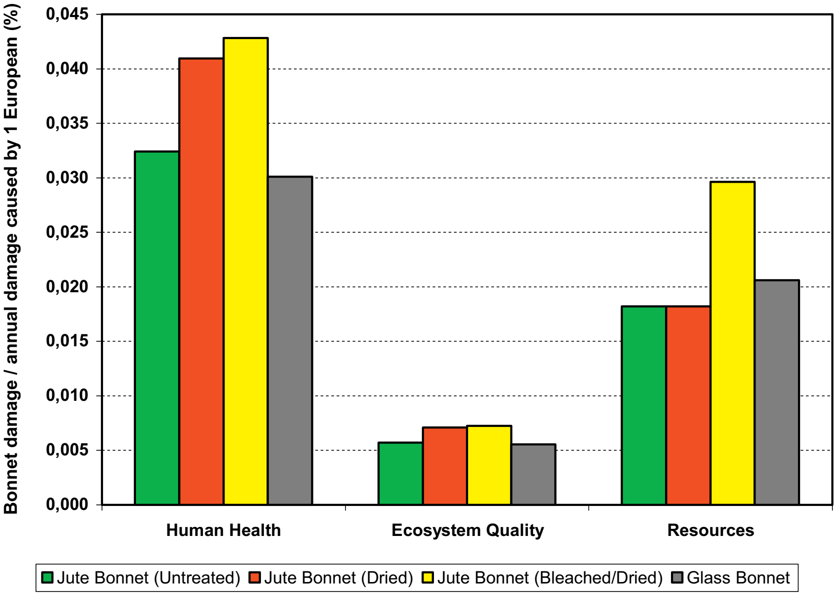

Fig. 3. Damage categories of the bonnets (Production Phase).

Table 5
Damage categories of the bonnets (Production phase).

Damage category	Jute bonnet (Untreated)	Jute bonnet (Dried)	Jute bonnet (Bleached/ Dried)	Glass bonnet
Human health	0.03241	0.04095	0.04284	0.03011
Ecosystem quality	0.00571	0.00710	0.00725	0.00556
Resources	0.01820	0.01820	0.02963	0.02062

Table 6
Impact categories of the bonnets (Production phase).

Impact category	Jute bonnet (Untreated)	Jute bonnet (Dried)	Jute bonnet (Bleached/Dried)	Glass bonnet
Carcinogens	0.00037	0.00037	0.00038	0.00027
Respiratory organics	0.00047	0.00061	0.00062	0.00045
Respiratory inorganics	0.03017	0.03846	0.03997	0.02805
Climate change	0.00139	0.00150	0.00186	0.00133
Radiation	1.319E-05	1.319E-05	1.320E-05	8.992E-06
Ozone layer	8.827E-07	8.827E-07	8.828E-07	2.230E-06
Ecotoxicity	0.00069	0.00069	0.00070	0.00082
Acidification/ Eutrophication	0.00481	0.00620	0.00635	0.00454
Land use	0.00020	0.00020	0.00020	0.00020
Minerals	0.00030	0.00030	0.00030	0.00012
Fossil fuels	0.01791	0.01791	0.02933	0.02050

3. Bonnet's life cycle inventory (LCI)

In this work, the LCA evaluation structure was performed using the SimaPro 7.0 software [33] and based on Eco-Indicator 99 [37] and its baseline damage and impact categories (Table 2).

Where,

- Disability Adjusted Life Years index (DALY) is the total amount of ill health, due to disability and premature death, attributable to specific diseases and injuries. It is also used by the World Health Organization;
- Potentially Disappeared Fraction (PDF) express the fraction of species that has probability of no occurrence in a region due to unfavorable conditions over a certain area during a certain time;
- MJ surplus is the surplus energy needed for future extractions of minerals and fossil fuel.

3.1. Inventory of the jute fibers extraction

Jute is well known in the Amazon Water Basin region in north of Brazil. In the 1930s the plant was introduced in Brazil by Mr. Ryota Oyama being initially cultivated by Japanese immigrants for producing handcraft goods. Later it became the most important source of revenue for local communities [38].

According to the Castanhal Têxtil Inc., which is the biggest producer of goods made of jute in Latin America, from the cultivation of the plant to fiber refining all of operations related to the jute are completely based on handwork by several small farmer communities along the Amazon River. Thus, phases such as cultivation, harvesting, mercerizing, drying and fiber refining were assigned without impacts. Still according to the supplier, the fields of jute do not need irrigation as long as annual precipitation is greater than 2200 mm, this condition was assumed in the present LCA. The soil does not need preparation since the river provides its humus and all of nutrients for plants during its overflowing.

After the harvesting the stems need to be decorticated to extract the fibers. This is done by maceration in the river for about 8–10 days due to the hot weather of the region, which promotes an easy fermentation of the stems, and then, extraction of the fibers. After that, the fibers are dried under canopies in the sun without chemical substances and rolled into bales. The raw fibers are then transported by trucks and/or coasters from farmer communities to the Castanhal Inc. (about 300 km) where the fibers are finally carded into jute fabrics (bi-axial or multi-axial). Table 3 provides all data of the jute cultivation obtained from Castanhal Inc. and used in this study.

3.2. Inventory of the composites and buggy production

After the production of the bi-axial jute fabrics, they are transported about 3100 km by truck from Castanhal Inc. in Pará State

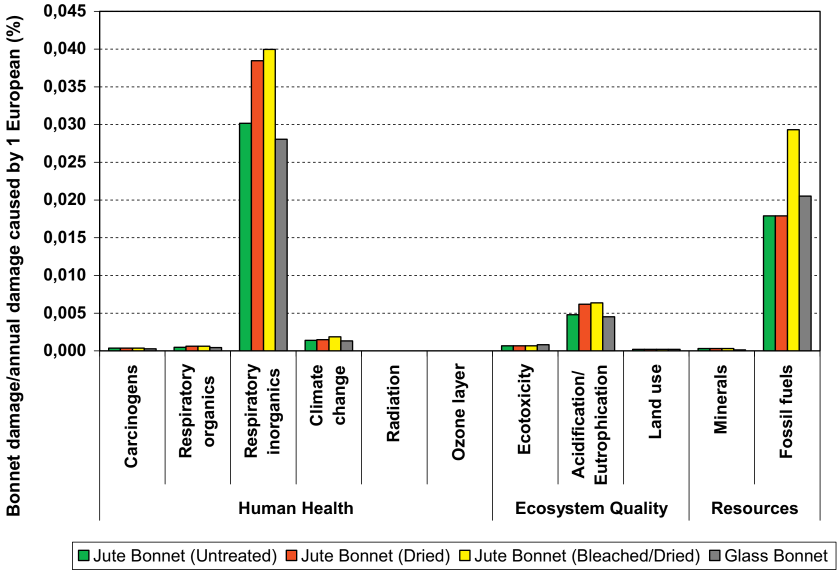

Fig. 4. Impact categories of the bonnets (Production Phase).

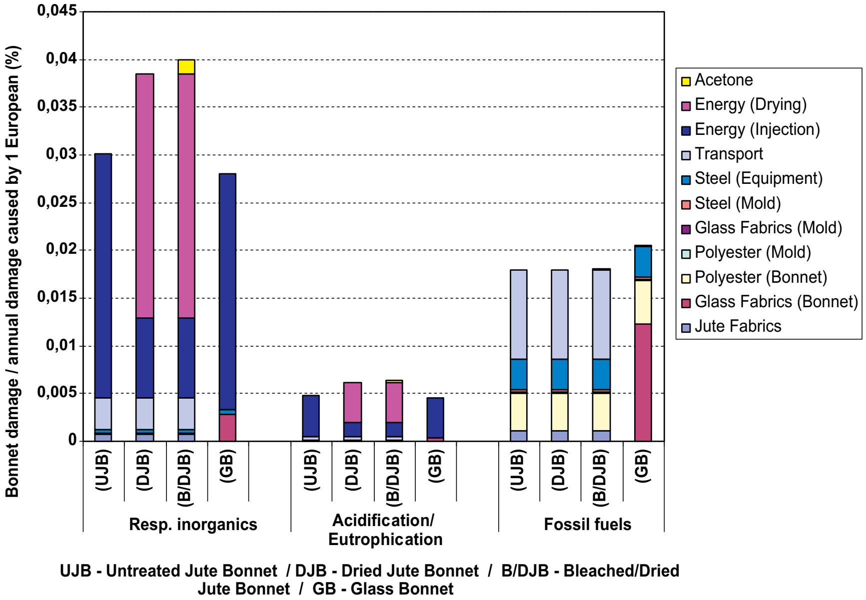

Fig. 5. Source of the impact categories of the bonnets (Production Phase).

(north of Brazil) to the Ancel Inc. in São Paulo State (southeast of Brazil) to produce the buggy's bonnets. Otherwise, bi-axial glass fibers are transported from Owens Corning Inc. to Ancel Inc. for about 20 km, since both companies are placed in the same city (Rio Claro) in São Paulo State. According to Castanhal Inc. each truck loads holding 28 tons of jute fabrics, and then, the same truck was assigned as transport of the glass fibers.

The bonnets made of both jute/polyester and glass/polyester composites are produced in São Paulo by RTM process, which is a very popular process in the automotive and aerospace industries to produce large and complex parts [39]. It has gained popularity in the preparation of fiber material composites due to its high efficiency and good reproducibility in which several types of polymeric matrix can be used in this process as long as their viscosity is low enough to ensure a proper wetting of the fibers reinforcement.

Before the injection of the bonnets, some untreated jute fabrics were treated according Alves [32] to increase the wetting behavior of the fabrics with apolar polyester, and thus to improve the adhesion fibers/polymer. Different treatments were also applied by others authors to get better the interface and to analyze the effects of those treatments only on the mechanical properties of the natural composites, due to the hydrophilic feature of the vegetable fibers [40–42]. In the first drying treatment, some jute samples were dried overnight (12 h) at 140 °C. In the second bleaching/drying treatment, other jute samples were previously soaked in acetone (technical grade) during 24 h, and then, they were dried according to the first treatment. After that they were arranged in the mold and compressed by a warm press. The same procedure was performed to produce the glass bonnet. To achieve the complete closing of the mold the ideal pressure of the press was for jute bonnets about 4–5 bars, while for glass bonnet it was 3.5 bars. Polyester matrix was then mixed with 0.25% in volume fraction of PMEK. The matrix mixture was allowed to pass through the mold, thus different optimization of injection pressures were obtained for each type of fibers (glass and jute). After 1 h curing, each bonnet

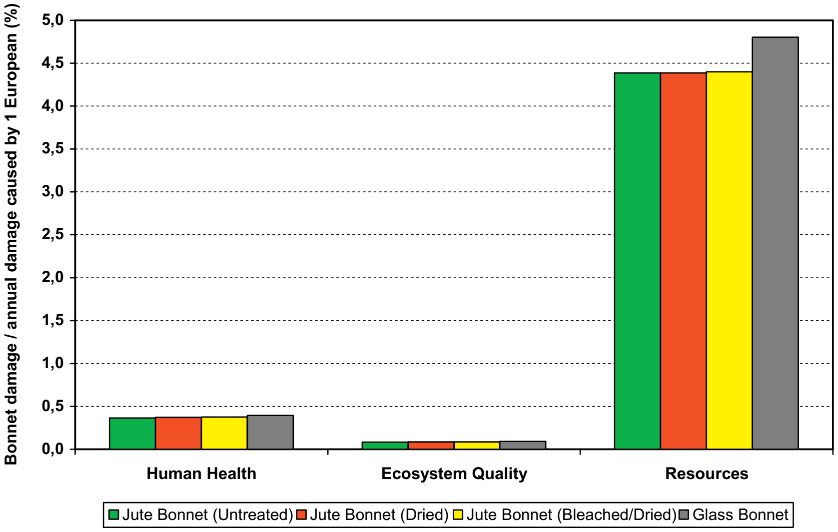

Fig. 6. Damage categories of the bonnets (Use Phase).

Table 7
Damage categories of the bonnets (Use phase).

Damage category	Jute bonnet (Untreated)	Jute bonnet (Dried)	Jute bonnet (Bleached/ Dried)	Glass bonnet
Human health	0.36529	0.37383	0.37572	0.39440
Ecosystem quality	0.08450	0.08589	0.08604	0.09179
Resources	4.38789	4.38789	4.39931	4.80267

Table 8
Impact categories of the bonnets (Use phase).

Impact category	Jute bonnet (Untreated)	Jute bonnet (Dried)	Jute bonnet (Bleached/Dried)	Glass bonnet
Carcinogens	0.01392	0.01392	0.01394	0.01510
Respiratory organics	0.00142	0.00156	0.00157	0.00149
Respiratory inorganics	0.29200	0.30030	0.30180	0.31459
Climate change	0.05697	0.05707	0.05743	0.06215
Radiation	0.00079	0.00079	0.00079	0.00085
Ozone layer	0.00019	0.00019	0.00019	0.00021
Ecotoxicity	0.01444	0.01444	0.01444	0.01587
Acidification/ Eutrophication	0.02606	0.02745	0.02760	0.02779
Land use	0.04400	0.04400	0.04400	0.04813
Minerals	0.00671	0.00671	0.00671	0.00714
Fossil fuels	4.38117	4.38117	4.39260	4.79553

was extracted from the mold and allowed to post cure at a room temperature for 300 h. Afterwards, all of enclosures of the buggy are assembled with others components and finally the vehicle is finished. Since the final trimming and assembly of the vehicle are the same for either reinforced composite, these phases were not considered in the LCA, even the production of the remaining parts and/or components of the buggy were not taken into consideration. The set of inputs of the bonnet production was recorded and used as input for the environmental analysis and are given in Table 4. The higher volume fraction of the jute fibers on the bonnet is due to their larger diameter of filaments (40 μm) by comparing with glass fiber filaments (14 μm). The total energy consumption is related to the Brazilian energy system [34].

3.3. *Inventory of the use phase of the buggy and the final disposal of its enclosures*

For the use phase the fuel consumption was taken into account to identify how influential is the replacement of the current material (GFRP) for the lighter jute fiber composites. Through the lower density of the jute fibers in comparison to glass fiber, it was possible to calculate the percentage of reduced weight of the bonnet made of jute fibers (about 15%) and of whole vehicle (0.048%). In this sense, based on literature [43,44], the decreasing fuel consumption of the buggy due to the use of the jute bonnet was estimated at about 0.029%, which means about 7.71 L (5.55 kg) for an expected life of 265,500 km. This expected use phase life is based on Sindipeças reports [45] in which is established the average life of a Brazilian vehicle of about 20 years and its average annual use of about 13,275 km/year [46]. It was estimated a current fuel consumption of about 10 km/L for a total weight of the buggy of about 600 kg. In this sense, the fuel consumption assigned to the bonnets made of glass and jute fibers was respectively about 64.36 kg and 58.81 kg taking into account the density of the petrol at 0.72 kg/L. In regards to the scenario of the final disposal of the enclosures, it will be explained later in disposal section.

4. Bonnets LCA: results and discussion

As explained above, LCA were performed to the bonnet of the buggy vehicle made of untreated and treated jute fiber composites and their results were compared themselves to analyze the environmental effects of the treatments and against the current bonnet made of glass fiber composites. LCA was divided in four steps such as from raw materials to production, use phase (fuel consumption), final disposal and the total life-cycle. Thus, the analysis provides a detailed understanding about the environmental impacts related to each phase, showing the most pollutant in the total life-cycle of the bonnet, the influence of the fibers in the life-cycle of each bonnet even the treatments of the jute fibers.

4.1. *Production phase*

Fig. 3 and Table 5 present the normalized comparison of the overall damage categories obtained from all inputs involved until the production of the bonnets. The normalized values express the percentage damage caused by the functional unit comparing with

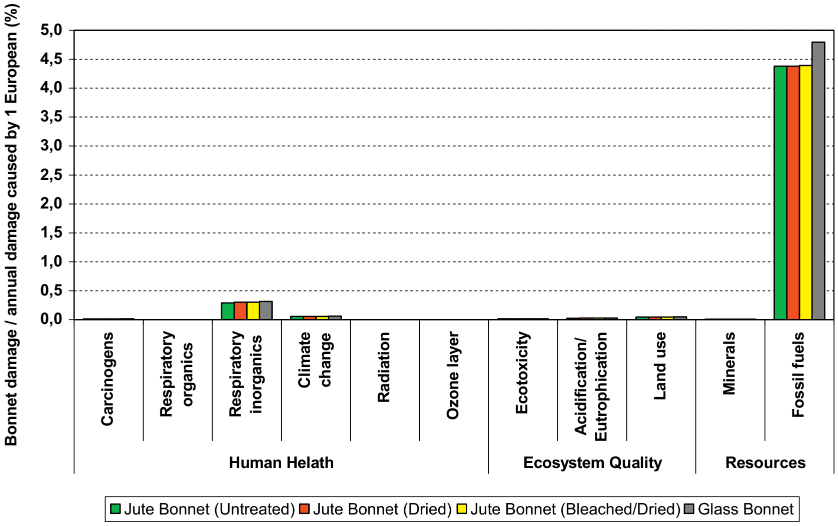

Fig. 7. LCA Impact categories of the bonnets (Use Phase).

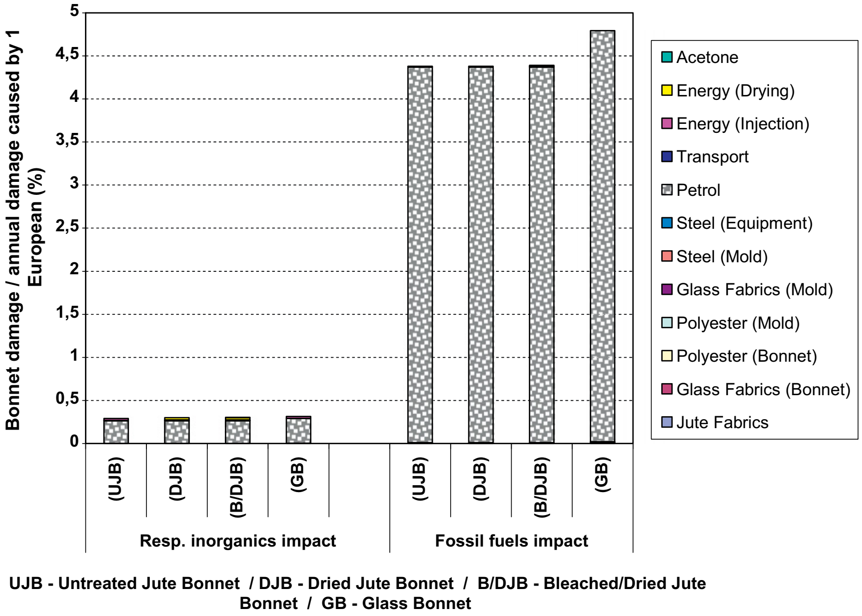

Fig. 8. Source of the impact categories of the bonnets (Use Phase).

the annual damage caused by one European person. It means that for instance the highest value of the bleached/dried jute bonnet causes 0.043% of the damage caused by one European person during one year. Results show that related to the total damage caused by environmental impacts raised from bonnets, human health category presents the highest damage for all bonnets, even the environmental impacts of the untreated jute bonnet cause larger damage (about 8%) than glass bonnet, while the dried and bleached/dried jute bonnets are larger than damage caused by glass bonnet about 36% and 42%, respectively. Related to the ecosystem quality, it has lowest contribution to the total damage caused by bonnets. Untreated jute bonnet also raises larger damage than glass bonnet (about 3%), while dried and bleached/dried jute bonnets cause about 28% and 30%, respectively, more damage than those caused by glass bonnet. In regards to the natural resources, among other categories it has a medium influence in total damage raised by bonnets. However, in this category untreated and dried jute bonnets have better environmental performance than glass bonnet (about 12%), while bleached/dried jute bonnet causes higher resources damage than glass bonnet (about 44%).

Among other causes, Fig. 4 shows that the highest human health damage regarding the bonnets is raised mainly by respiratory inorganics impacts (Table 6). These impacts are raised consequently by energy consumption (about 85%) related to the production of the fabrics of fibers and the bonnets, taking into account the Brazilian electric system which is based on hydroelectric source (89%). Related to each bonnet, respiratory inorganics also shows the highest contribution to bonnet's damage. Among themselves, the contribution is similar the human health, since jute bonnets require more energy consumption to their production comparing with glass bonnet, besides the extra energy consumption to the drying of the both treated jute bonnets. Related to the natural resources, they are raised by fossil fuel impacts for all bonnets. Regarding to the untreated and dried jute bonnets, the resources impacts are provided mainly by the fuel used by transports (52%), the consumption of fuel to produce polyester matrix (22.5%) and by the steel of equipments and tools (19.4%). In this damage category, despite their higher journey transport and higher use of energy to dry and to produce the bonnets, they have lower contribution to impacts than glass bonnets. Due to the production of glass fibers that is high fuel consumption, it raises about 60% of glass bonnet fossil fuel impacts, while polyester and steel represent 23% and 17%, respectively. Otherwise, bleached/dried jute bonnet has the highest fossil fuel impact due to the manufacturing of the acetone (40%), it requires a higher fuel consumption even comparing with the production of the glass fibers, while transports represent 32% and polyester and steel represent 14% and 12%, respectively. Related to the ecosystem damage, for all bonnets, it is raised mainly by acidification/eutrophication due to the electric energy consumption. Since the jute bonnets required more energy to produce and to treat them, they cause higher and significant damage to the ecosystem damage. Fig. 5 shows the sources of the respiratory inorganics, acidification/eutrophication and fossil fuel impact categories of the bonnets.

In this context and until the production phase, the glass bonnet has the best environmental performance than all jute bonnets, since untreated and treated jute bonnets require more energy consumption and logistic transports. Both treatments have large influence to the environmental performance of the bonnets, becoming them more pollutant than untreated jute bonnet, even than glass bonnet. The remaining impact categories have no significant influence on the environmental damage caused by bonnets, representing less than 5% of the total damage (Table 6).

Table 9
Experimental recycling of the composite materials.

Bonnet	Shredding (W)	Ball grinder (W)	Strainer (W)	Total energy consumption (kW)	Total time (min)	Recycling efficiency (%)
Jute	183.33	66.25	4.17	0.25375	25	11.85
Glass	366.67	66.25	8.33	0.44125	35	11.11

Table 10
Disposal scenarios of the composite materials.

Scenario			
Bonnet	Recycling (%)	Incineration (%)	Landfill (%)
Jute fibers	12	8	80
Glass fibers	11	9	80

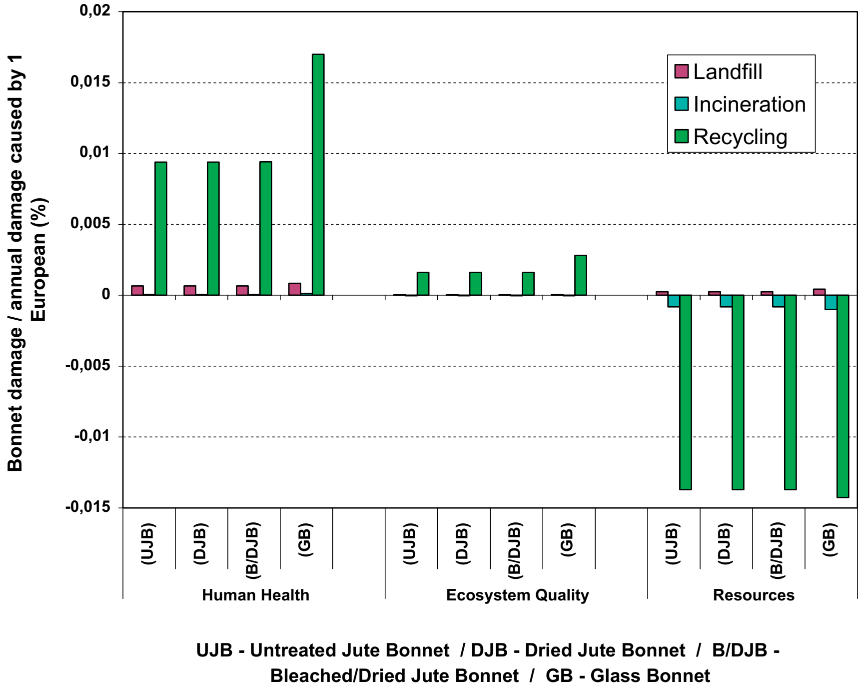

Fig. 9. Damage categories of the bonnets (Disposal Phase).

4.2. *Use phase*

Most of the environmental impacts of a vehicle are related to its use phase due to the fuel consumption [47,48]. In this sense, as explained in section 4.3 the bonnets made of glass and jute fibers were added with about 64.36 kg and 58.81 kg of petrol, respectively, taking into account the density of the petrol at 0.72 kg/L. The higher mass of petrol assigned to the glass bonnet is due to its higher weight that implies directly an increase of the fuel consumption of the vehicle.

In the use phase all damage categories of bonnets present significant changes (Fig. 6 and Table 7). Results show that the addition of the petrol implied a very large increase of the total damage caused by bonnets comparing with their damage caused until the production phase (about 8500%). In this phase the resources damage category has the highest contribution for the total damage of each bonnet, presenting a significant difference comparing with others damage (about 1000%). Unlike the production phase, glass bonnet causes larger environmental damage (average 9%) than damage raised by untreated and treated jute bonnets for all categories. On the other hand, jute bonnets present no significant difference among themselves in any damage category (maximum 0.50%). These results are due to the high influence of the petrol on the environmental impacts.

According Fig. 7 and Table 8 the highest values of the natural resources damage were caused by fossil fuel impact category which is raised (about 97%) during the use of the vehicle due to the fuel consumption (Fig. 8). Respiratory inorganics impact category that causes human health damage represents about 2.5% of the total damage, and for all bonnets it was raised mainly by fuel consumption of the vehicle (about 90%) and by energy consumption to produce the bonnets (10%). The contribution of both impact categories to the total damage is similar to their respective damage category (resources and human health), in which for all categories jute bonnets also causes lower impact than glass bonnet. Among jute bonnets, all of them has the same contribution to the total damage for fossil fuel impact, while in respiratory inorganics impact both treated jute bonnets has an increase of about 3% comparing with untreated bonnet. Even though, it shows that the treatments do not imply a decrease of the environmental performance of the bonnets, since the use of fuel is the most influential impact.

Table 11
Damage categories of the bonnets (Disposal phase).

		Landfill	Incineration	Recycling
Human health	(UJB)	0.00066	6.902E-05	0.00940
	(DJB)	0.00066	6.902E-05	0.00940
	(B/DJB)	0.00066	6.902E-05	0.00942
	(GB)	0.00084	0.00013	0.01700
Ecosystem quality	(UJB)	3.082E-05	−4.117E-05	0.00162
	(DJB)	3.082E-05	−4.117E-05	0.00162
	(B/DJB)	3.082E-05	−4.117E-05	0.00162
	(GB)	5.444E-05	−4.511E-05	0.00280
Resources	(UJB)	0.00025	−0.00082	−0.01371
	(DJB)	0.00025	−0.00082	−0.01371
	(B/DJB)	0.00025	−0.00082	−0.01371
	(GB)	0.00044	−0.00099	−0.01427

UJB-Untreated jute bonnet/DJB-Dried jute bonnet/B/DJB-Bleached/Dried jute bonnet/GB-Glass bonnet.

Table 12
Impact categories of the bonnets (Disposal phase).

Impact category	Jute bonnet (Untreated)	Jute bonnet (Dried)	Jute bonnet (Bleached/Dried)	Glass bonnet
Carcinogens	−7.916E-05	−7.916E-05	−7.916E-05	−7.285E-05
Respiratory organics	0.00018	0.00018	0.00018	0.00031
Respiratory inorganics	0.00947	0.00947	0.00949	0.01694
Climate change	0.00056	0.00056	0.00056	0.00080
Ozone layer	−7.432E-07	−7.432E-07	−7.432E-07	−7.620E-07
Ecotoxicity	−3.895E-05	−3.895E-05	−3.895E-05	−0.00012
Acidification/ Eutrophication	0.00165	0.00165	0.00165	0.00293
Minerals	−1.394E-05	−1.394E-05	−1.394E-05	−3.344E-07
Fossil fuels	−0.01427	−0.01427	−0.01427	−0.01483

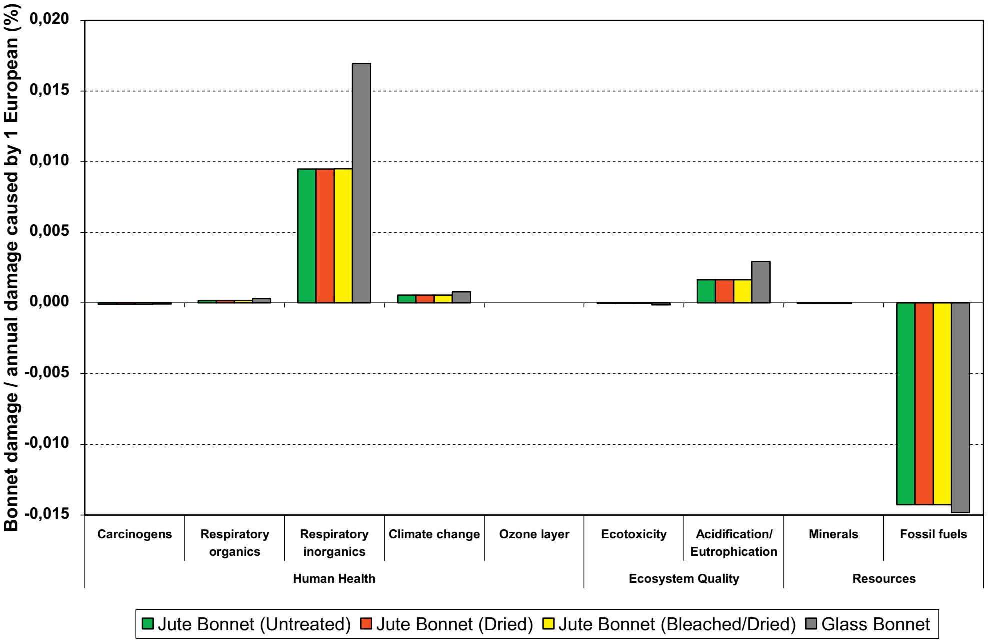

Fig. 10. Impact categories of the bonnets (Disposal Phase).

Unlike the previous phase, in the use phase untreated and treated jute bonnets have best environmental performance than glass bonnet. The greater weight of the glass bonnet implies its higher fuel consumption, hence its higher environmental impacts, since the impacts raised by fossil fuel are much more influential in the total damage than impacts raised by large transports and treatments of the jute fibers. Results pointed out how pollutant the use phase is in the life-cycle of a mobility product, it is important to note that fuel has a great influence in all impact categories of all bonnets. However, other impact categories have no significant influence on the total damage (Table 8).

4.3. Disposal phase

Recycling of composite materials has already been developed [49], however it still demands high energy consumption and it is

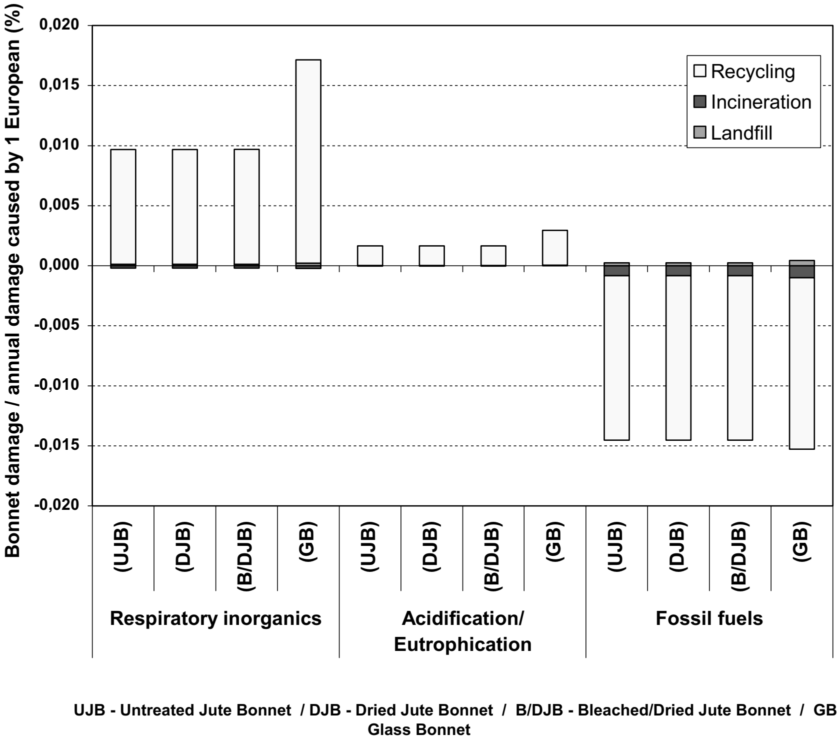

Fig. 11. Source of the impact categories of the bonnets (Disposal Phase).

Table 13
Source of the impact categories of the bonnets (Disposal phase).

		Landfill	Incineration	Recycling
Respiratory inorganics	(UJB)	0.00013	−0.00019	0.00954
	(DJB)	0.00013	−0.00019	0.00954
	(B/DJB)	0.00013	−0.00019	0.00956
	(GB)	0.00022	−0.00021	0.01693
Acidification/Eutrophication	(UJB)	2.076E-05	−1.357E-05	0.00164
	(DJB)	2.076E-05	−1.357E-05	0.00164
	(B/DJB)	2.076E-05	−1.357E-05	0.00164
	(GB)	3.681E-05	−1.129E-05	0.00291
Fossil fuels	(UJB)	0.00025	−0.00082	−0.01369
	(DJB)	0.00025	−0.00082	−0.01369
	(B/DJB)	0.00025	−0.00082	−0.01369
	(GB)	0.00044	−0.00099	−0.01427

UJB-Untreated jute bonnet/DJB-Dried jute bonnet/B/DJB-Bleached/Dried jute bonnet/GB-Glass bonnet.

Table 14
Damage categories of the bonnets (Total life-cycle).

Damage category		Production phase – Use phase	Disposal phase
Human health	UJB	0.36529	0.01012
	DJB	0.37383	0.01012
	B/DJB	0.37572	0.01015
	GB	0.39440	0.01797
Ecosystem quality	UJB	0.08450	0.00161
	DJB	0.08589	0.00161
	B/DJB	0.08604	0.00161
	GB	0.09179	0.00281
Resources	UJB	4.38789	−0.01428
	DJB	4.38789	−0.01428
	B/DJB	4.39931	−0.01428
	GB	4.80267	−0.01483

UJB-Untreated jute bonnet/DJB-Dried jute bonnet/B/DJB-Bleached/Dried jute bonnet/GB-Glass bonnet.

not economically feasible due to its low efficiency. In this study, a mechanical recycling was performed with bonnets and specimens used to characterize the mechanical behavior of composites in experimental tests. The mechanical recycling aimed to find the efficiency of reuse the composite materials and then to define a recycling scenario based on experimental data. Table 9 shows the energy consumption of each step of the experimental recycling, the total time to perform that and the recycling efficiency of both composite materials. Regarding to their recycling efficiency, the results confirm the low efficiency to recycling GFRP (11%), even vegetable composites present this low feature of recycling (12%). Nevertheless, the energy consumption required to recycle glass composites is about 74% larger than energy required by jute composites recycling.

In the mechanical recycling, first of all the composites were fragmented in pieces with diameters of about 4 mm, using a shredding machine EWZ200 obtained from Erdwich (Germany), then the fragmented fraction of the composites was crushed using a ball grinder Pulverisette 06.102 obtained from Fritsch (Germany). Finally, the crushed material was strained to obtain the composite powder which was used as fillers to produce new bonnets. It was performed using an Analysette 3 PRO with a strainer of 325 mesh (45 µm) also obtained from Fritsch (Germany). The remaining material from recycling (GB-89%, JB-88%) was assigned to incineration and landfill scenarios based on Brazilian governments reports [35,36] which state that 0.2% of the total Brazilian waste is incinerated, 59.5% is collected but not treated and 20% is neither collected or controlled. Therefore, energy recovery was assumed for the incineration scenario. Final disposal scenarios assigned for bonnets are displayed in Table 10.

As observed in Fig. 9 and Table 11, for all bonnets the human health category has the highest contribution to the total damage caused by bonnets (about 80%), while ecosystem quality present about 20% of the total damage. On the other hand, resources damage category presents another type of contribution to the total damage, it is well known as “avoided impact”, in which the use of new raw materials and natural resources are avoided by, e.g., the reuse of energy and/or materials.

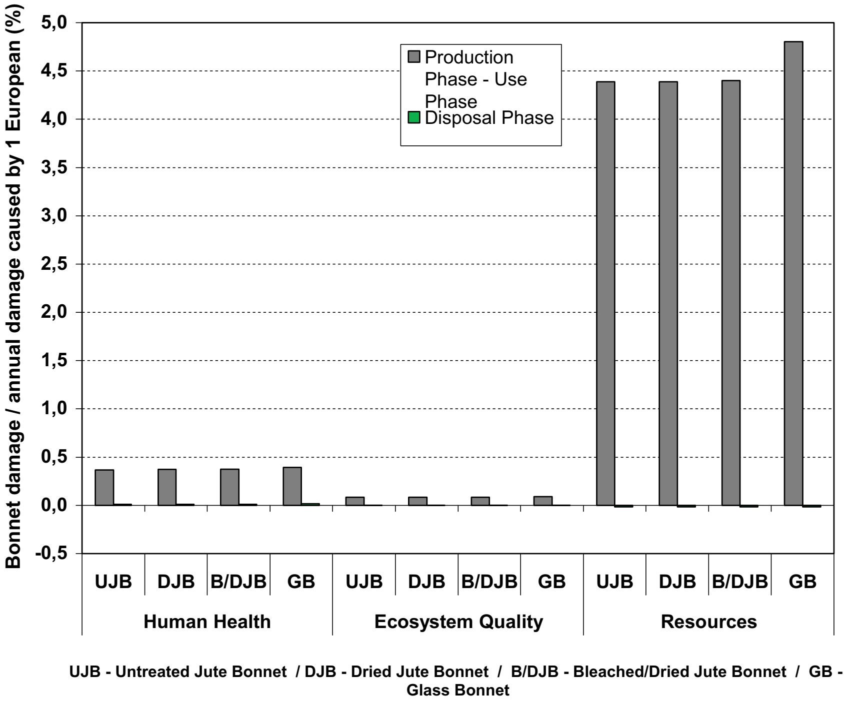

Fig. 12. Damage categories of the bonnets (Total Life-Cycle).

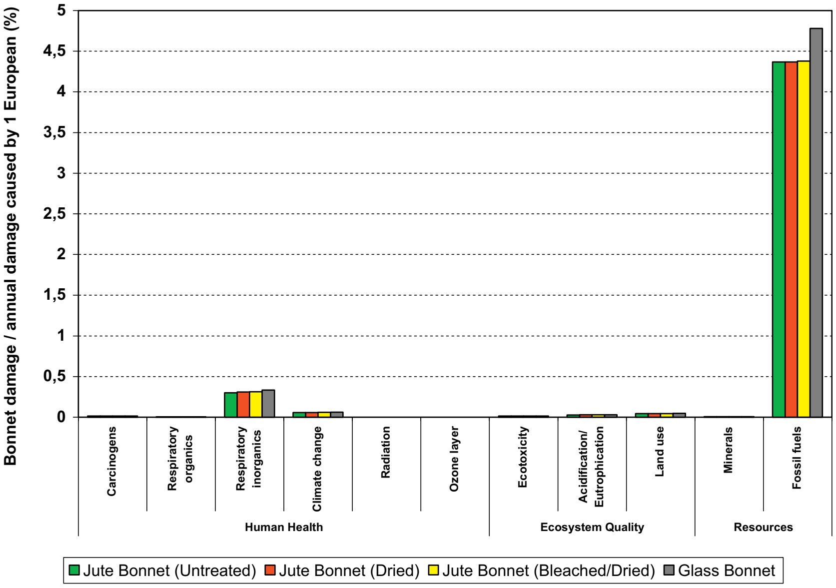

Fig. 13. Impact categories of the bonnets (Total Life-Cycle).

In regards to the end of life of the bonnets, for all damage categories the environmental impacts (positive or negative) present the highest contribution for the total damage caused by bonnets, even for avoided impacts. Being they raised by recycling scenario that also presents a significant difference comparing with the remaining disposal scenarios. Disposal phase shows glass bonnet as the most pollutant among the composites, causing larger environmental damage (average 75%) than those raised by untreated and treated jute bonnets. Since the energy consumption required to recycling glass bonnet was 74% larger than energy required to the jute bonnets. However, glass bonnet also presents larger avoided impacts than jute bonnets (about 4%). Moreover, jute bonnets present no difference for any damage category among themselves. The remaining disposal scenarios have no significant influence on the total damage caused or avoided by bonnets, representing just about 6% of them (Table 12).

Fig. 10 shows the impact categories of the bonnets in their end of life and their contribution to the total damage. The human health damage is raised mainly by respiratory inorganics impact, while ecosystem quality and resources categories are raised basically by acidification/eutrophication and fossil fuel impacts respectively. Among these impacts, respiratory inorganics and acidification/eutrophication are raised by recycling scenario due to its high energy consumption which implies almost 100% of their respective damage category (Fig 11). However, despite the respiratory inorganics and acidification/eutrophication impacts, the resources damage category contributes with the reduction of the total damage of the bonnets, since 100% of its impacts are avoided environmental impacts related to the recycling of the polyester matrix. Damage resources category is raised basically by fossil fuel (about 97%) due to the recycling of the composites (Table 13), which avoid the use of natural resources to produce raw polymeric matrices to manufacture new bonnets or other automotive components made of composite materials.

Despite the low percentage assigned to recycling scenario due to its low efficiency of reusing the composite materials, it is the most influential scenario which implies almost 100% of the impacts in the phase of the bonnets. Besides the recycling disposal, incineration also contributes to the avoided impacts for all impact categories, since energy recovery was assumed to that, while landfill is the lower influential scenario, causing impacts for all categories (Fig. 11). Regarding to the bonnets, like to damage categories, for impact categories, glass bonnet is the most pollutant composite average 75% higher than jute composites, and at the same time it raises more avoided impacts (about 4%), comparing with untreated and treated jute bonnets. Moreover, jute bonnets present no difference for any impact category among themselves.

Results point out that the efficiency reached to the bonnets is almost the feasibility limit of the recycling scenario. For jute bonnets, the sum of the impacts assigned is lower than the sum of the avoided impacts (about 20%), so recycling shows to be a positive choice for vegetable composites. Nevertheless, for glass bonnet results are the opposite, the avoided impacts are lower than impacts (about 30%), point out that recycling scenario is not environmentally feasible to GFRP (Table 12).

4.4. Total life-cycle

Regarding to the life-cycle of the buggy's bonnets, Fig. 12 and Table 14 show the total damage causes by the environmental impacts in their total life-cycles, as a balance between raised and avoided impacts.

Overall, it is clear that use phase is significantly more pollutant than production and disposal phase (about 1000%), in fact disposal

Table 15
Inputs of the enclosures.

Enclosure	Injection flow (cc/min)	Volume of the fiber (%)	Mass of the bonnet (kg)	Mass of the fiber (kg)	Total fuel consumption (kg)
Jute (untreated and treated)	45	31	93.5	32.9	3013
Glass	50	21	110	40	3504

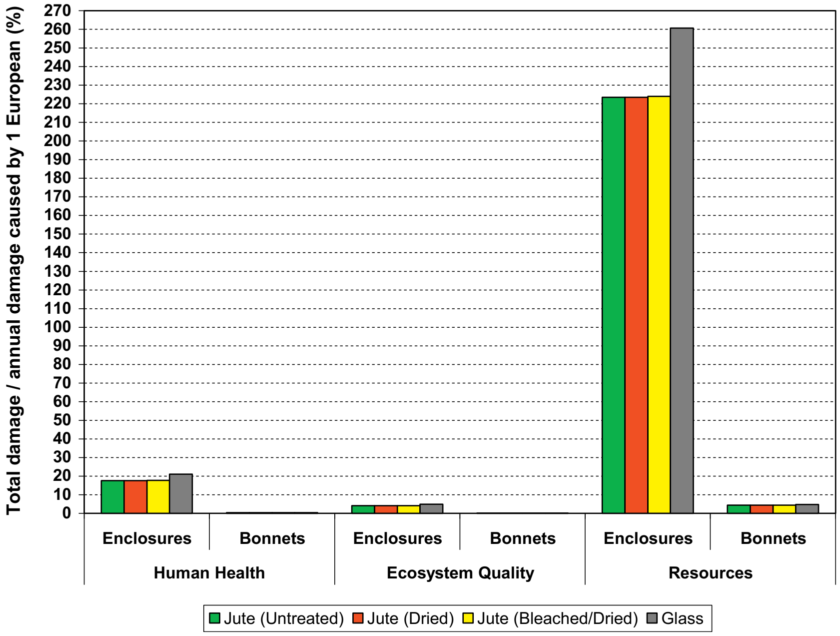

Fig. 14. Damage categories of the total enclosures and bonnets (Total Life-Cycle).

phase represents just about 3% of the total damage, being raised by energy consumption of the recycling scenario. The significant impacts are raised by use phase (about 97%), since its the values are very close of total life cycle and most of impacts are related to the resources damage category due to the consumption of fossil fuel, while 3% are related to the production phase and its energy consumption, which raises respiratory inorganics impacts (Fig. 13). In the whole life cycle, glass bonnet presents larger environmental damage (average 9%) comparing with damage raised by all jute bonnets, due to its higher weight and fuel consumption. About the treatments, Table 13 shows that comparing to the untreated jute bonnets, both drying and bleaching/drying treatments decrease the environmental performance of bonnets at about 1% and 2%, respectively. In other words, both treatments are high pollutant until the production phase, in which dried and bleached/dried jute bonnets have 18% and 42% more environmental impacts than untreated jute bonnets. After use phase, the fuel consumption becomes the treatments no significant to the total damage. Finally, results show that in spite the high importance of the production and disposal phases for the life cycle of vehicles, in this buggy case study the use phase is more pollutant and more important to focus the design improvements. It confirms researches [47,48] which state the use phase as the most pollutant phase of a vehicle.

4.5. Total life cycle of buggy's enclosures

The LCA of the study was based on the part level of the buggy (bonnet), and remaining enclosures of the vehicle was not taken into account. However, it is important to highlight that in a buggy the environmental damage raised by whole polymeric enclosures are much higher than in a conventional vehicle. It occurs due to, unlike conventional vehicles in which just about 15% of its total weight is made of plastics [50], in a buggy vehicle all enclosures and panels are made of composite materials.

In this context, this section of the study was performed to analyze the contribution of the whole enclosures of the buggy to the environmental damage in its total life cycle, comparing with the contribution of the bonnet. Thus an average weight of about 110 kg to the glass enclosure and 93.5 kg to the untreated and treated jute enclosures were assigned as functional unit. Like bonnet's case study, to the simulation of the enclosures, the assigned percentage of fiber reinforcements was at 31% for jute fibers and 21% for glass fibers, each one has the same numbers of bi-axial jute or glass fibers with the same stacking sequence [(0/90), (45/−45), (0/90)]. They were also assumed to be produced using the RTM process. As the use phase is absolutely dominant throughout the overall life cycle of the buggy, the weight of the glass enclosure was taken from Ancel database, while the weight of the jute enclosures and the fuel consumption for all of them was obtained based on section 3.3 reasoning (Table 15). The remaining inputs related to the production and disposal phases were assigned as the same of the bonnets.

Fig. 14 shows that compared with all environmental impacts during production, use and recycling of the bonnet, the replacement of glass fibers by jute fibers for all of enclosures has a great effect. Using jute instead of glass fibers, the impacts on natural resources damage raised by the total enclosures is almost three

Table 16
Damage categories of the enclosures and bonnets (Total life-cycle).

	Part	Jute (Untreated)	Jute (Dried)	Jute (Bleached/Dried)	Glass
Human health	Enclosures	17.642	17.651	17.747	21.013
	Bonnets	0.375	0.384	0.386	0.412
Ecosystem quality	Enclosures	4.132	4.133	4.141	4.902
	Bonnets	0.086	0.087	0.088	0.095
Resources	Enclosures	223.510	223.510	224.082	260.605
	Bonnets	4.374	4.374	4.385	4.788

Table 17
Mechanical properties of the bonnets.

Composite sample	Fiber arrangement	Maximum strain (%)	Elastic modulus (GPa)
GB	Bi-axial	0.69	8.81
	Multi-axial	0.57	4.59
UJB	Bi-axial	1,52	1,85
	Multi-axial	0.81	3.19
DJB	Bi-axial	0,57	5,29
	Multi-axial	0.6	4.13
B/DJB	Bi-axial	0.77	4.9
	Multi-axial	0.87	2.96

times the annual damage caused by 1 European, while the impacts caused by bonnets is just about 5% of the annual European damage. Table 16 shows that the average damage caused by glass bonnets for all of damages categories is of about 10% higher than damages caused by all jute bonnets. On the other hand, damage caused by total glass enclosures is about 18% higher than damage caused by total jute enclosures. It means that replacing all of glass fibers for jute fibers improve the environmental performance of the buggy at about 15%, while jute means an improvement of about 9%. Thus, a much more significant effect could be reached by switching to light-weight design of vehicles by design of composite materials. About treatments, unlike the treated jute bonnets in which treatments decreased in the environmental performance of them (about 1% and 2%), for total enclosures, there are no differences among their environmental performance. It proves that treatments of jute fibers are a great choice, improving the mechanical performance of the jute composites without imply environmental impacts.

4.6. *Social, economical and technical analysis*

The main core of this buggy case study was to analyze the environmental impacts related to the replacement of the composite reinforcements to produce buggy's enclosures. Nevertheless, in the development processes of products there are other important requirements to ensure their success. In this sense, qualitative and quantitative results will be presented to show how important are jute fibers in the whole aspects of the buggy's project.

In regards to the social requirements, jute fiber plays an important role from the cultivation of the plant to the production of the bonnet. In its cultivation phase jute means income source to the local farmer communities contributing to the sustainability of the region, avoiding the rural exodus hence its social problem in industrial cities. In the production phase, jute fiber causes fewer health risks and skin irritation than glass fibers for the employees that are directly involved in the production of the components.

Related to the economical advantages, for Ancel Reinforced Plastics, jute fibers cost about seven times less than glass fibers, while production costs are almost the same, since it is possible to produce either jute or glass composites with almost the same setup and production processes. Using jute fibers also implies lower fuel consumption, so it means an economical advantage for owners of the buggy. Still, the potential global market for natural fibers in the automobile industry is expected to increase. Nowadays in the USA more than 1.5 million vehicles are the substrate of choice of bio-fibers such as kenaf, jute, flax, hemp and sisal and thermoplastic polymers such as polypropylene and polyester [51].

Regarding to the technical parameters (Table 17), all of bonnets were produced according to section 3.2 and tested under ASTM standards (D-3039/D-790/D-256). The results show that the superficial treatments of the jute fibers improved the mechanical properties of their composites; e.g., the elastic modulus of the treated bonnets increased about 250% while their maximum strain decrease about 70%, proving the improvement of the interface polyester/jute. These results are closer of glass composites which become jute composites feasible to produce technical parts, without imply more environmental impacts as presented before.

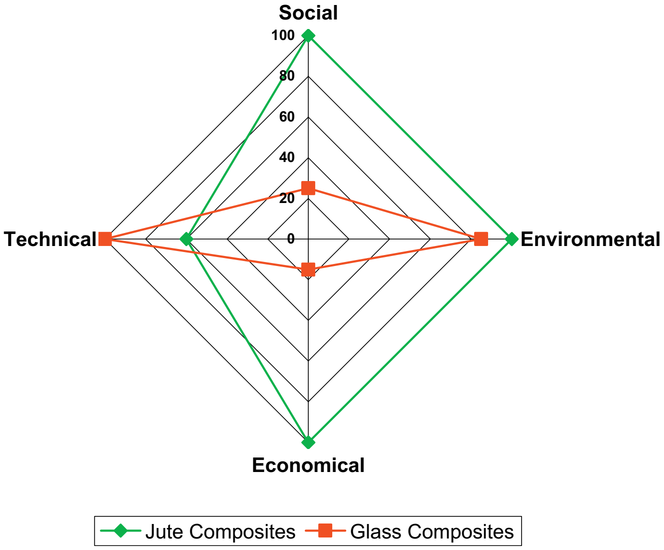

Fig. 15. Performances of the bonnet's aspects.

Finally, Fig. 15 shows a semi-quantitative overview comparison of the all aspects of the bonnets based on sustainable design procedure [9] and on the triple bottom line approach [52] added to the technical aspects, since the ecodesign of materials needs to reach technical requirements. The better results were assumed as 100% while other values are the fraction them. Related to the technical parameters, the elastic modulus of the jute composites are 40% of the glass composites, then it was assigned as 60%. Social parameters is a qualitative aspect, it was based on the social effects of the fibers reinforcement in all of phases, jute fibers present better aspects in all of them, which glass fibers just present some advantages in raise industrial employment. Environmental aspects, was presented by LCA that jute fiber implies an increase of about 15% of the performance of the composites, while the economical aspects, jute fibers cost about seven times less than glass fibers. In this sense, is possible to note that jute fibers have many advantages in the replacement of glass fibers to reinforce composite materials. It is possible to observe that jute composites related to the four aspects, present the better overview performance than glass composites.

5. Conclusions

This study presents the LCA analysis of the replacement of glass fibers by jute fibers as reinforcement of composite materials to produce automotive structural components. In regards to the composite materials, buggy case study demonstrated that jute fiber composite presents the best solution enhancing the environmental performance of the buggy's enclosures, hence improving the environmental performance of the whole vehicle. Despite the fuel consumption becoming lower using jute fibers, due to the weight reduction of the vehicle, LCA pointed out some unknown impacts in production and disposal phases of the bonnets, specifically related to the logistic transports of the jute fibers and the recycling scenario of the bonnets. It gave to design team an overview scenario of the problem, besides traditional inputs usually used in the design of products, providing results that help the design team to make decisions, still working in partnership with suppliers to improve the logistic of the jute fibers and focusing the more pollutant phases to prevent potential environmental effects. Finally, this case study is a first step towards the sustainability of the Brazilian buggy industry, since it can be an example for other companies to manufacture more sustainable buggies. It can even drive users awareness for more environmentally friendly consumption behavior.

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