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Bio-based versus traditional polymer composites. A life cycle assessment perspective

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A B S T R A C T

A comparative LCA between an eco-sandwich made of bio-based epoxy resin (SuperSap 100/1000) and natural fibers against a traditional sandwich made of epoxy/glass-fibers was carried out. The main purpose and contribution of this study is the exploration of the eco-efficiency of this new material which featured applications span from naval to automotive and building sectors. To a minor degree, it is also a contribution in the sense that it provides life cycle inventory data on composites, which as yet are scarce in the LCA community. Life cycle assessments of bio-based polymers have shown favourable results in terms of environmental impacts and energy use compared to petroleum-based products. However, calculation of these impacts always depends on the system and boundary conditions considered during the study.

1. Introduction

Sandwich panels are widely used in composite structures because of their ideal combination of high flexural stiffness and low weight. Structural sandwich applications normally rely on the use of honeycombs made of aramid paper or aluminum as core materials while, for semi-structural applications, PVC and balsa wood cores are the preferred choice. The skin materials can vary from glass to carbon fiber/polymer composites. Glass and carbon fibers may both negatively affect the environment in terms of the energy and resources consumption needed for their production. Natural fibers are perceived as green materials that can be produced starting from renewable materials and with production techniques that consume lower energy relative to synthetic fiber production techniques (Corbière-Nicollier et al., 2001).

LCA has been applied to a large range of natural fiber composites for assessing the environmental aspects and potential impacts associated with the products (e.g. Riedel and Nickel, 2003). Results demonstrate that natural fiber composites offer environmental advantages such as reduced dependence on non-renewable energy/material sources, lower pollutant emissions, lower greenhouse gas emissions, enhanced energy recovery, and end of life biodegradability of components (Joshi et al., 2004; Dornburg et al., 2004; Mohanty et al., 2002). However, Dissanayake et al. (2009a, 2009b) have presented data that suggest that flax fibres may require equivalent or higher energy consumption due to heavy reliance on agrochemicals (when all burdens are assigned to the primary product as recommended by Ekvall and Finnveden, 2001). Le Duigou et al. (2011) use alternative apportionments to generate lower energy input values with their Table 2 stressing the differences between the respective independent analyses which return comparable data.

The objective of the present study is to evaluate the environmental impacts associated to the production of a sandwich composite where the core is made of granulated (see §2.3.2.2 below) cork panel and the external skins are made of bio-derived epoxy resin reinforced with hemp fibers (Fig.1). The future goal will be to understand if the use of eco-materials in the sandwich formulation is able to considerably reduce the environmental burdens without compromising the mechanical performance. An LCA of the cork panels used, produced by Syfar s.r.l (Messina in Sicily) was also carried out. Cork is a product of great ecological value (Rives et al.,

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Table 1
Thermal insulation properties of cork and polyurethane.

Core materials	Thermal properties		
	Thermal conductivity, λ (W/mK)	Thickness (m)	Thermal resistance (m^2K/W)
Cork	0.05	0.02	0.4
Polyurethane	0.022	0.01	0.45

2012a, 2012b), with many features that make it very interesting from a sustainability perspective. In addition to its low emissions and the great potential for capturing CO_2, it generates economic revenues, provides jobs and development in rural areas, and allows many environmental services such as forest preservation, biodiversity conservation and wildfire prevention (Pereira, 2007; Pereira and Tomé, 2004).

2. Methodology

2.1. Goal and scope definition as used in ISO 14040

The present work is a cradle-to-manufacture study in order to evaluate the main environmental impacts related to the production of an eco-sandwich panel containing cork, hemp and bio-based epoxy resin as natural materials. A comparison with a traditional sandwich composite made of glass fiber, petroleum based epoxy resin and polyurethane, was carried out. The Life Cycle Assessment study was developed according to the ISO 14040 and 14044 methodology (ISO 14040, 2006; ISO 14044, 2006) and used the Simapro 7.2 software (SimaPro 7.2, 2012).

2.2. Functional unit

An eco-sandwich panel sized (0.400 × 0.400 × 0.02 m) is the functional unit for this study (Fig. 1). Assembling the granulated cork panel with hemp mats and epoxy resin produces the composite sandwich by means of resin infusion under flexible tooling (RIFT I) (Summerscales and Searle, 2005). For comparisons, a traditional sandwich made of polyurethane core and using glass fibre for resin reinforcement, was also studied. In order to provide a congruous comparison we prepared both sandwich panels with the same thermal insulation properties by varying the amount of insulating materials (cork and polyurethane). The thermal resistance was fixed, according to the Italian law for building applications, $U < 0.4$ m^2K/W as reported in Table 1. The thermal conductivity of cork was evaluated by means of a heat flow-meter HFM 436 Lambda (Netzsch). The thermal conductivity of polyurethane was found in literature (Mingheng et al., 2006).

Mechanical tests are being carried out and will be used for a future paper. A theoretical evaluation is included in the present work, in Table 2.

2.3. Boundaries and description of the system

2.3.1. System boundaries

A cradle (field) to manufacture (factory) study was carried out considering raw materials production (consisting of cork forestry and granulated cork panels production; hemp cropping and hemp mat production) and eco-sandwich manufacture as boundaries. Waste scenarios were also discussed and landfill was included in the LCA. Primary data were collected for the manufacturing process of the cork and the eco-sandwich; literature data were used for the hemp cultivation and production (González-García et al., 2010; La Rosa et al., 2013) and data from the Ecoinvent v2.2 database were used as a last resort (PRè-Product Ecology Consultants, 2012).

Table 2
Mechanical properties of an eco-sandwich and a traditional sandwich. Sandwich dimensions and weights are reported in Table 4.

Sandwich	Tensile strength (MPa)	Tensile modulus (MPa)	Compressive strength (MPa)	Compressive modulus (MPa)
Eco				
- Cork	[a]0.23	[a]32	[a]0.83	[a]1.22
- Hemp mat	552.6	28000		
- SuperSap resin	60.0	3074		
- Composite (hemp mat 25% + SuperSap resin 75%)	[c]94.58	[c]4820		
[d]**Flexural Stiffness**: $D = E \cdot I = 6995$ (N m^2)				
Traditional				
- Polyurethane foam	[b]5.6	[b]172	[b]2.65	[b]130
- Glass fibre	2400	70000		
- Epoxy resin	69.0	3500		
- Composite (E-glass mat 25% + Epoxy resin 75%)	[c]271.3	[c]8990		
[d]**Flexural Stiffness** $D = E \cdot I = 4083$ (N m^2)				

[a] Data provided by the Syfar company.
[b] Data source: http://www.matweb.com/search/QuickText.aspx?SearchText=polyurethane%20foam.
[c] Tensile modulus and tensile strength of reinforced resins were evaluated through the Madsen model (Madsen and Lilholt, 2003; Madsen et al., 2007) considering voids percentage value Vp = 0.88%.
[d] Flexural stiffness was evaluated through the following equation (Biron, 2007) where E_f and E_c are the moduli of elasticity of the faces (index f) and the core (index c).

$$D = E_f\frac{bt^3}{6} + E_f\frac{btd^2}{2} + E_c\frac{bc^3}{12}$$

2.3.2. Description of the manufacturing process

2.3.2.1. Cork forestry: cork reproduction and extraction in a Sicilian forest. Cork consists of the thick outer bark of the cork oak (Quercus suber). Harvesting cork is the operation of removing bark from the tree and is repeated every 9 years. It is always carried out between May and August (from 15 May to 15 August according to the regional law), by a team of workers. The flowchart in Fig. 2a reports the main steps of the extraction process. Typical Mediterranean wild plants create a deep barrier to working operations therefore clearing of the underwood area by means of a tractor is required as the first operation. A manual bark stripping operation, by expert workers using axes, takes place. The stripper makes long cuts in order to extract large pieces of cork. The raw cork material obtained is moved to the road (Rives et al., 2012a).

Fig. 1. Eco-sandwich with core in granulated cork and skins in hemp/bio-resin.

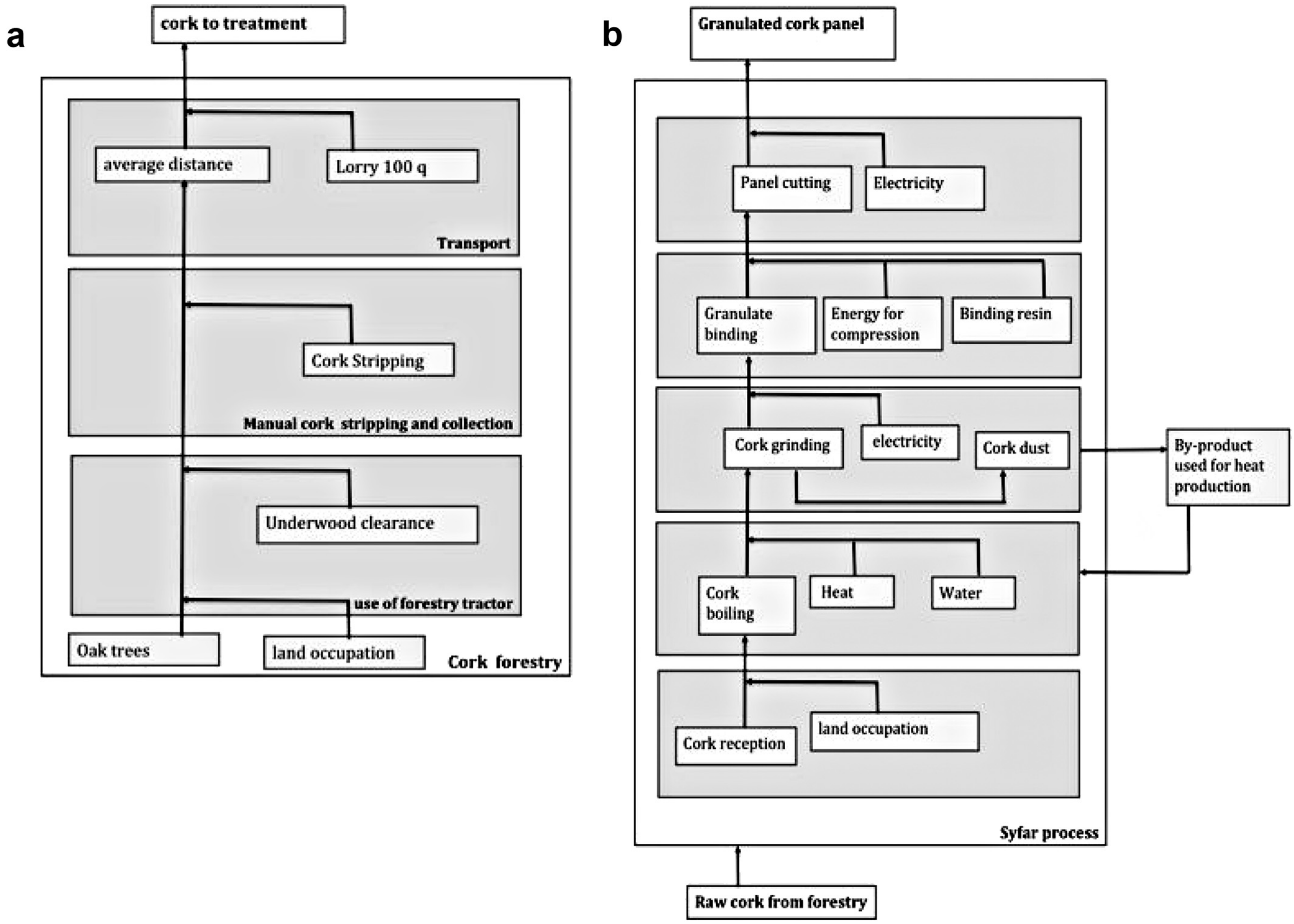

Fig. 2. a. Flowchart of cork forestry process. b. Flowchart of Syfar process for cork panel production.

2.3.2.2. Cork industry: production of granulated panels by the Sicilian company Syfar s.r.l. The Syfar industrial process is summarized with a flowchart in Fig. 2b. All data were provided by the owner of the Syfar company. Raw cork from forestry is transported to the Syfar plant by means of 10 tonne lorries. Average distance from cork oak forests to the Syfar industrial plant was considered to be 70 km. The facility treats 25.000 t of virgin cork per year. The raw cork after reception is stored for about 6 months in an open air space. Subsequently, cork is boiled in clean water at 95 °C for 1 h, in order to clean the cork, extract water-soluble substances, and improve cork flexibility and elasticity. Thus, the cork is stabilized and is ready for the grinding process. This operation basically consists of breaking up the pieces of raw cork into small particles of between 0.25 and 8 mm by using an industrial grinder. These particles are then sieved

Table 3a
Inventory data to produce 2.500 tonnes of raw cork.

Cork forestry inventory	Quantities
Materials	
- Cork yield per year	2.500 tonnes
- Land use	625 ha
- Fungicide	No
- Colouring	No
- Water	No
Transport	
- 10 tonne lorry from forest to industry	Km 70 (average distance from forest to industry) 625 ha
- Tractor for underwood clearance	Negligible
Workers	
- Stripping	5.500 working days
- Collection	(from 15 May to15 August)

Table 3b
Inventory data to produce a tonne of granulated board. Primary data were provided by the owner of the Syfar.

Cork industry inventory	Quantities	Costs (euro)
Materials and Energy consumption		
a) Raw cork thermal treatment		
- Raw cork	1200 kg	300 €/ton
- Water	200 l (from a well)	No extra costs
- Heat	350.000 kcal/h (totally produced by burning scraps)	No extra costs.
b) Cork grinding process		
- Electricity from grid	45 kwh	9 € (0.2 €/kwh) used for heating
- Cork dust (by-product)	200 kg (burned for heating)	
c) Binding process		
- Electricity from grid	30 kwh	6 € (0.2 €/kwh)
- Heat	1000 kcal/h	From cork dust. No extra costs.
- Binding (without solvent)	0.5%	Negligible
Number of workers	n. 1	25.000 € per year
Occupied land	30.000 m^2	–

Table 4
Inventory data for sandwich manufacture. Materials weight and dimensions.

Sandwich manufacture	Size (m)	Weight (kg)	Density (kg/m3)	Quantities
Materials				
Eco				
- Cork	0.4 × 0.4 × 0.02	0.413	191	1 panel
- Hemp mat	0.6 × 0.6 × 0.005	(0.1365x2) = 0.273	76	2 mats
- SuperSap resin	–	1.31	1120	–
Traditional				
- Polyurethane foam	0.4 × 0.4 × 0.01	0.046	28.7	1 panel
- Glass fibre	0.6 × 0.6 × 0.003	0.281	260	1 mat
- Epoxy resin (Prime 20LV)	–	1.31	1.123	–
	Quantity			
Resin infusion process (RIFT I)	1.125 kWh Electricity consumption for using a vacuum pump (power 0.750) for 1.5 h			
Process scrap production	- Polyethylene bag and pipe for the infusion: 0.1 kg - Epoxy resin: 0.26 kg			
	Distance			
Transport	- Epoxy resin and glass fibre transport from Spain to Italy (Sicily): 1500 km, lorry > 32t and 600 km, lorry 7.5-16t - Hemp transport from England to Italy (Sicily): 1500 km, lorry > 32t and 600 km, lorry 7.5-16t			
	Type			
Waste scenario	Landfill			

using densimetric tables. Separation by density classes makes it possible to sort out the heavier particles, which are reprocessed. Fine particles with dimensions lower than 0.25 mm are removed as dust throughout the process and are all used as an energy source. Cork dust production is evaluated at about 20% of the initial raw cork. It is considered a by-product in the environmental analysis. All the scraps produced in the process (cork dust and granulated scraps) are burned to obtain the necessary heat for the boiling process. Finally, the different granulate fractions are mixed with a small amount of binder under pressure in order to obtain the granulated panels. Cutting and packaging are the final operations depending on the user's specifications.

2.3.2.3. Composite manufacture: production of eco-sandwich panels in our laboratories

2.3.2.3.1. Production of hemp/epoxy resin skins. The external skins of the sandwich were manufactured by using hemp mats to reinforce a plant based bio-epoxy resin, SuperSap 100/1000 (Entropy). All material used are commercial and purchased from several producers. Hemp mat was purchased from Hemcore Ltd., United Kingdom. According to the technical data sheet, Hemcore BioMat is a completely natural and fully biodegradable hemp fiber fabric. The hemp fiber is extracted in a factory in Essex from hemp straw grown exclusively for Hemcore on British farms. The hemp is grown without the use of herbicides or pesticides and the fibers are extracted in a clean, chemical free and waste free process. The SuperSap Entropy System was supplied by Ferrer Dalmau, Barcelona, Spain. As opposed to traditional epoxies that are composed primarily of petroleum-based materials, SuperSap formulations contain up to 50% of bio-based renewable materials sourced as co-products or from waste streams of other industrial processes, such as wood pulp and bio-fuels production.

2.3.2.3.2. Materials transport. The distance between the country of origin of the raw materials and the country of production of the composite final product was accounted in the analysis.

2.3.2.3.3. Production of the eco-sandwich. The eco-sandwich is manufactured using the resin infusion under flexible tooling (RIFT I) technique that uses vacuum driving resin flow. Materials (cork panel and hemp mats) are laid dry into the bag closed and the vacuum is applied before resin is introduced. Once a complete vacuum is achieved, resin is sucked into the laminate via carefully placed tubing. Vacuum infusion provides a number of improvements over other techniques such as hand lay up. These benefits include better fiber-to-resin ratio, less wasted resin, very consistent resin use, and cleaner process.

2.4. Life cycle inventory (LCI)

According to the general framework provided by ISO 14040-44 standards, an inventory analysis was carried out to quantify the environmentally significant inputs and outputs of the systems

Table 5a
Potential environmental impacts associated to a tonne of raw cork extracted from forestry (method CML 2000 v2.0/West Europe, 1995).

Impact category	Units	Raw cork
Abiotic Depletion (ADP)	kg Sb eq.	0.0531
Acidification Potential (AP)	kg SO_2 eq	0.0304
Eutrophication Potential (EP)	kg PO_4^--eq	0.00874
Global Worming Potential	kg CO_2 eq	7.83
Ozone Layer Depletion Potential (ODP)	kg CFC11 eq	1.06E-6
Human Toxicity Potential (HTP)	kg 1.4 DB eq	18
Freshwater Aquatic Ecotoxicity Pot. (FAETP)	kg 1.4 DB eq	1.11
Marine Aquatic Ecotoxicity Pot. (MAETP)	kg 1.4 DB eq	2.39E3
Terrestrial Ecotoxicity Potential (TETP)	kg 1.4 DB eq	0.0257
Cumulative Energy Demand (CED)	MJ eq	114

Table 5b
Potential environmental impacts associated to a tonne of granulated cork panel manufactured by Syfar srl (method CML 2000 v2.0/West Europe, 1995).

Impact category	Units	Cork panel
Abiotic Depletion (ADP)	kg Sb eq.	0.214
Acidification Potential (AP)	kg SO_2 eq	0.106
Eutrofication Potential (EP)	kg PO_4^--eq	0.0479
Global Worming Potential	kg CO_2 eq	22.9
Ozone Layer Depletion Potential (ODP)	kg CFC11 eq	3.1E-6
Human Toxicity Potential (HTP)	kg 1.4 DB eq	34.2
Freshwater Aquatic Ecotoxicity Pot. (FAETP)	kg 1.4 DB eq	7.14
Marine Aquatic Ecotoxicity Pot. (MAETP)	kg 1.4 DB eq	1.5E4
Terrestrial Ecotoxicity Potential (TETP)	kg 1.4 DB eq	0.125
Cumulative Energy Demand (CED)	MJ eq	828

Table 6
Potential environmental impacts associated to 1 kg of hemp mat and 1 kg of glass-fibers production.

Impact category	Units	Glass fiber	Hemp mat
Abiotic depletion (ADP)	kg Sb eq.	0.02	0.004
Acidification potential (AP)	kg SO_2 eq	0.017	0.0026
Eutrofication potential (EP)	kg PO_4^--eq	0.04	0.0006
Global worming potential	kg CO_2 eq	2.95	0.531
Ozone layer depletion potential (ODP)	kg CFC11 eq	2.49E-7	6.88E-08
Human Toxicity Potential (HTP)	kg 1.4 DB eq	9.52	0.136
Freshwater Aquatic Ecotoxicity Pot. (FAETP)	kg 1.4 DB eq	0.684	0.0571
Marine Aquatic Ecotoxicity Pot. (MAETP)	kg 1.4 DB eq	1.46E3	131
Terrestrial Ecotoxicity Potential (TETP)	kg 1.4 DB eq	0.0412	0.00152
Land occupation (Ecological footprint)	m^2a	0.0692	1.54
Cumulative Energy Demand (CED)	MJ eq	51.3	8.89

under study, by means of a mass and energy balance. A life cycle inventory was carried out using different data sources. This LCA adheres to the ISO standards on data quality to help ensure consistency and reliability.

2.4.1. Data collection

Primary data were collected for the manufacture phase (cork forestry, cork industry, composite manufacture) as reported in Tables 3a, 3b and 4.

In the inventory of granulate cork panel production it can be observed that 1200 kg of raw cork were required to produce 1metric tonne of product. This is because about 20% of dust was produced during the manufacture process. This fraction of cork was mainly removed by suction during the processing operations and used as combustion fuel for the boiling operation and the compression/binding process. The substitution of other more harmful sources of energy with cork dust reduces the environmental impacts. Table 4 reports the quantities of materials used to manufacture an eco-sandwich; the scraps produced during the process; the electricity consumption due to the vacuum pump; materials transportation and landfill scenario.

2.4.2. Allocations and avoided impacts

- The raw cork extracted from the forests was transformed into granulated cork (about 80% yield by weight). Dust (about 20% by weight) was considered as a by-product as it can be used in the industry as fuel to heat and boil the raw cork. An allocation of 20% was assigned to the dust material in the analysis.
- The heat necessary for the boiling process was obtained from combustion of cork dust. It was considered that biomass use for energy generation is Ïcarbon neutralÓ over its life cycle because combustion of biomass releases the same amount of CO_2 as was captured by the plant during its growth (Cherubini et al., 2009). Therefore, it must be pointed out that this source of energy was renewable and that it avoided the environmental impact of using other non-renewable sources of energy.
- Water used for the boiling process comes from a private reservoir belonging to the Syfar. Wastewaters after boiling are purified and reused as process water. The company periodically checks basic parameters such as pH, COD, total nitrogen or suspended materials.

It must be noticed that some aspects of the Syfar process creates environmental benefits as described below:

- Heat required for the process is totally produced by burning the cork dust with no extra use of fuel;
- Part of the electricity is produced by a small photovoltaic system;
- Water is available from a well and is recycled several times;
- Transport of raw cork is on local scale (70 km). The distance to transport the cork from the Syfar

2.4.3. Quality data: geographical and local representativeness

Geographical representativeness describes the geographical area from which data for unit processes are collected to satisfy the goal of the study. Data for energy, materials, processes, and transportation are based on European sources. Glass fiber and resin production comes from several European producers and is considered to be average European production. Primary data were used for the manufacture phase at Syfar and our laboratories, as reported in Table 3a, 3b and 4; literature data were used for the hemp cultivation and processing; materials transport data were accounted according to the distance between countries. Temporal representativeness describes the age of data and the minimum length of time over which data are collected. The data applied to this study represent current products and

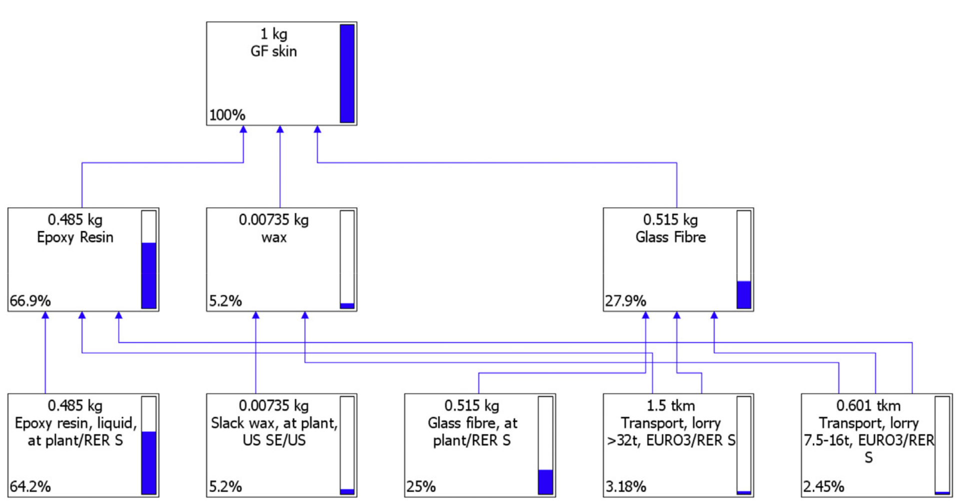

Fig. 3. Percentage of impact contribution for each components referring to the production of 1 kg of glass-fiber/epoxy resin composite.

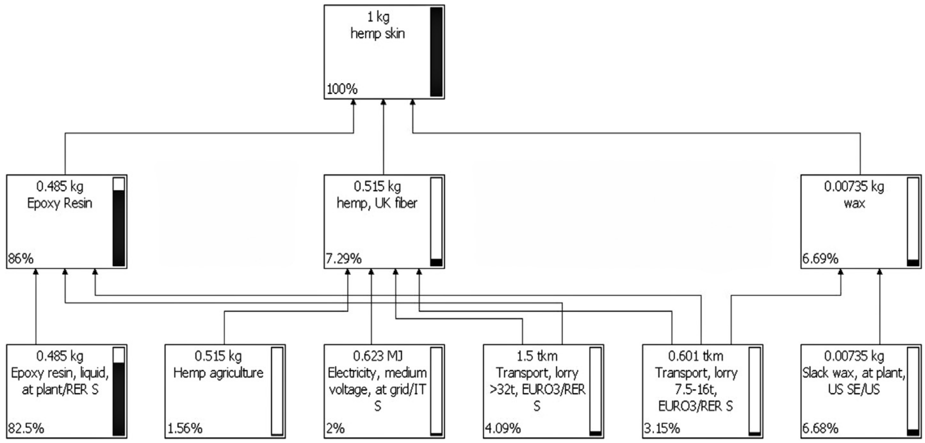

Fig. 4. Percentage of impact contribution for each components referring to the production of 1 kg of hemp/epoxy resin composite.

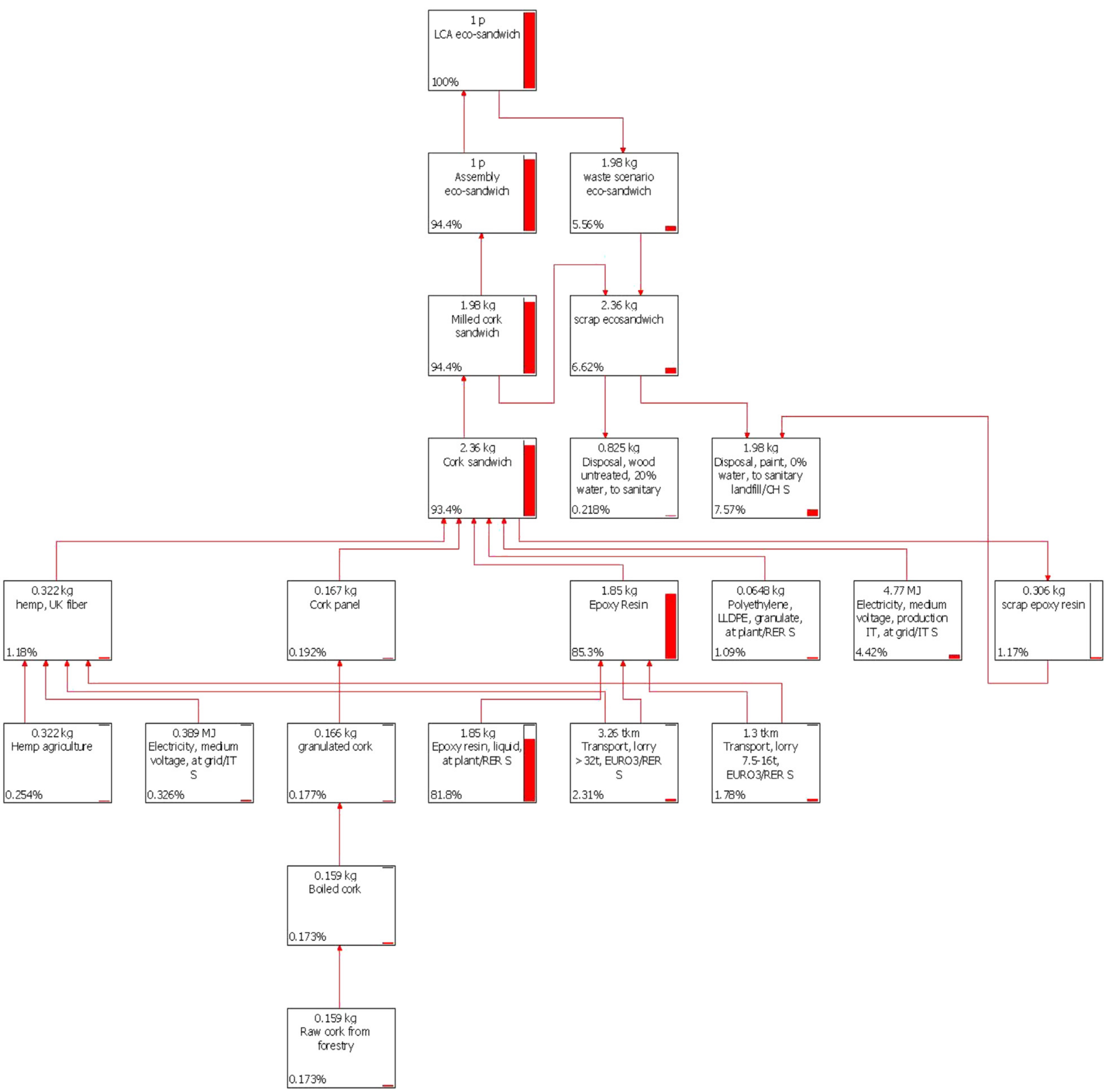

Fig. 5. Percentage of impact contribution evaluated for each components of the flowchart referring to the LCA of 1 eco-sandwich.

Table 7
Potential environmental impacts associated to 1 tonne of petroleum based epoxy resin and 1 tonne of plant-derived SuperSap Entropy resin.

Impact category	Units	Petroleum based-epoxy resin[a]	SuperSap Entropy[b]
Abiotic Depletion (ADP)	kg Sb eq.	59.4	0.01
Acidification Potential (AP)	kg SO_2 eq	40.3	25.44
Eutrofication Potential (EP)	kg PO_4^--eq	6.6	6.9
Global Warming Potential (GWP)	kg CO_2 eq	6663	4079
Ozone Layer Depletion Potential (ODP)	kg CFC11 eq	1.26E-6	0.00
Human Toxicity Potential (HTP)	kg 1.4 DB eq	490.44	545.17
Freshwater Aquatic Ecotoxicity Pot. (FAETP)	kg 1.4 DB eq	246.5	66.39
Terrestrial Ecotoxicity Potential (TETP)	kg 1.4 DB eq	29.1	228.63
Cumulative Energy Demand (CED)	MJ eq	2.16	1.90

[a] Environmental impact results obtained using data from Ecoinvent v.2 database.
[b] Environmental impact results purchased by Entropy resin.

practices averaged over one year. The granulated panels are currently used in several applications. Epoxy resins/hemp composites have been already applied in the pipelines of petrochemical industries (Cicala et al., 2009; La Rosa et al., 2013). The parts and materials lists are current and representative. Waste management practice for the eco-sandwich panels are current.

3. Results and discussion

The environmental impact assessment associated to the raw cork extraction, to cork panel production and to eco-sandwich manufacture are presented. Comparison with non-renewable materials (glass-fibers and petroleum based epoxy resin) and with a traditional polyurethane based sandwich will be performed in order to point out the environmental benefits of using an ecological approach in material design.

3.1. Cork sector life cycle impact assessment (LCIA)

Tables 5a and b report respectively the environmental impact assessment associated to a tonne of raw cork extracted from forestry and to a tonne of granulated cork panel manufactured by Syfar srl (LCA method CML 2000 v2.0/West Europe, 1995). It can be noticed that the cork extraction process contributes 34% of CO_2 emission and the cork panels production is 13.7% of Cumulative Energy Demand. However, it must be considered that carbon fixed by the cork oak forests was not taken into account because the tree is not destroyed by cork harvesting and CO_2 remains sequestered in the parent plant.

3.2. Glass-fibers versus hemp mats impact assessment

A comparison between the impact assessment associated to the production of 1 kg of glass-fibers and 1 kg of hemp mat is reported in Table 6. In this evaluation we consider that our glass fiber supplier is based in Germany and our hemp mat supplier is based in the UK. The distance of materials transportation is included in the evaluation. All impact categories are remarkably higher in glass-fiber production than in hemp mat production except for the category land occupation due to hemp cropping (land occupation: 0.0692 m2a for glass-fibers and 1.54 m2a for hemp).

In this case study we can state that hemp agriculture practice, even if it requires the occupation of arable land, has a positive impact in terms of soil quality improvement because hemp is used for crop rotation. Usually, another limit of renewable materials is that generally they score better than petrochemical polymers with regard to fossil energy use and greenhouse gas emissions while they score worse with regard to ecotoxicity and eutrophication (Weiss et al., 2012). In our case study this limit is overcome by the choice of using organic hemp that avoids the use of fertilization and pesticides. The magnitude of the environmental advantage also depends on the kind of application and obviously on the distance between the country of production of the materials and the country where they are used. Fig. 3 is a flowchart of the impact of each component involved in the production of an epoxy/glass-fiber

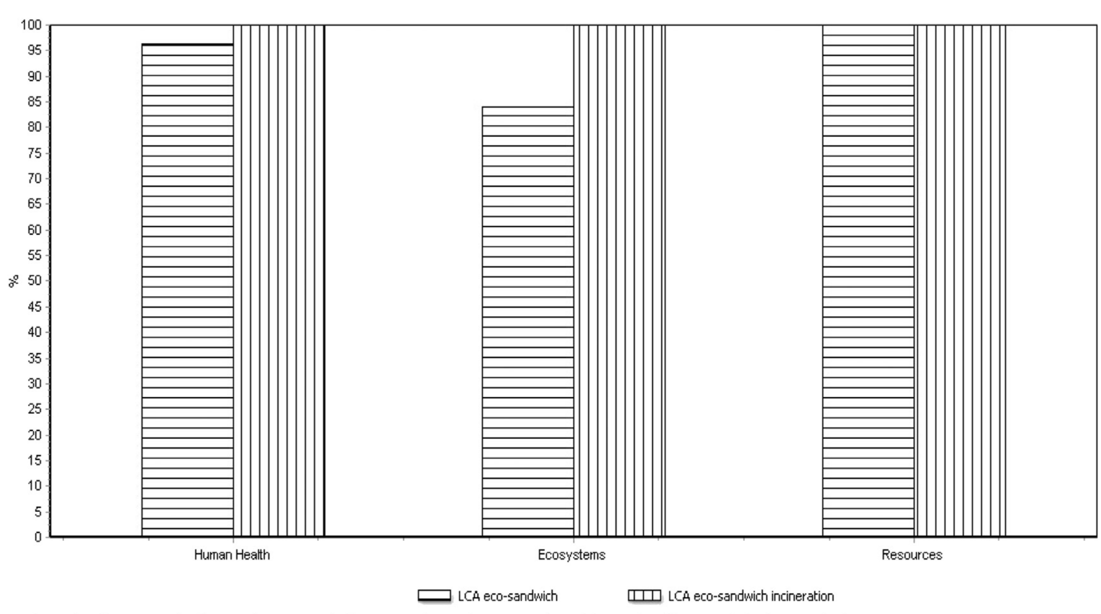

Fig. 6. Comparison of the eco-sandwich LCA with landfill scenario and with incineration scenario.

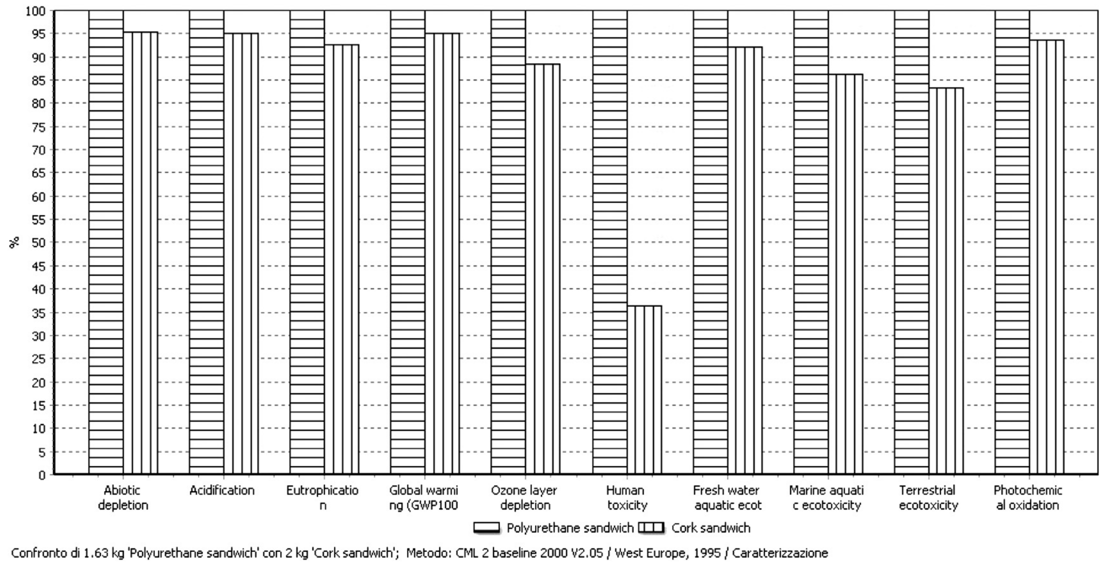

Fig. 7. CML impact comparison of polyurethane sandwich and cork sandwich. Inventory data associated with the bar chart are reported in Table 4.

composite through hand lay up technology. The major impact is associated to the epoxy resin (66.9%) while the impact due to the glass-fibers is 27.9%. Fig. 5 reports a flowchart relating to the hemp/epoxy hand lay up composite. The impact associated to the hemp mat is 7.29%. Consequently, the overall impact result of the hemp/epoxy resin is lower than the impact of the glass-fibers/epoxy resin. In order to further reduce the impact of the system we decided to replace the petroleum based epoxy resin with the SuperSap bio-based epoxy resin Fig. 4.

3.3. Petroleum based epoxy resin versus SuperSap Entropy resin impact assessment

Data reported in Table 7 show significant reductions in (a) Global Warming (GWP100), reflecting lowering of power consumption and of the consequent CO_2 and greenhouse gas emissions, and (b) abiotic depletion, being water consumption, for the SuperSap formulations. Furthermore, biomass sourced as a co-product or from waste streams of other industrial processes significantly reduces carbon footprint and does not compete with food sources.

3.4. Eco-sandwich impact assessment

The flowchart reported in Fig. 5 assembles all the steps required for the impact evaluation of the eco-sandwich manufacture. In this analysis, the cork panel manufacture impacts for 0.19% (total impact associated to the amount of cork panel used in the sandwich, 0.413 kg, as reported in Table 3); the hemp mat manufacture impacts for 1.18% (total impact associated to 0.273 kg of hemp as reported in Table 6). Road Transport of hemp mats from the UK to Sicily is the main contribution to this percentage, as shown in Fig. 5. The highest impact, as predictable, is due to the epoxy resin (85.3%). In the impact assessment reported in Fig. 5, the epoxy resin used is a standard petroleum based epoxy resin with data available in the Ecoinvent database. The substitution of a petroleum based epoxy resin with a plant-based epoxy resin reduces the impacts as seen in Table 7.

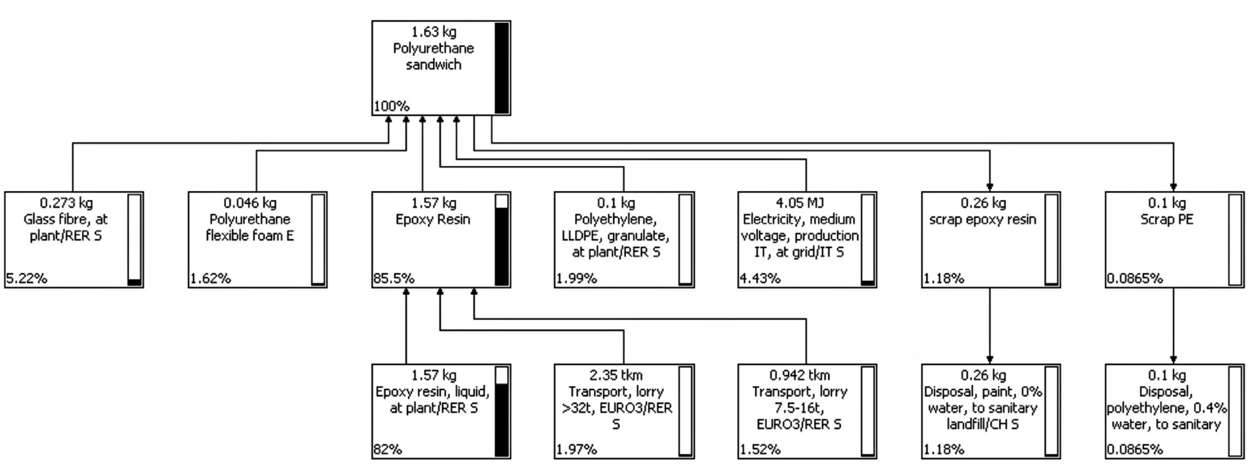

Fig. 8. Percentage of impact contribution for each components referring to the production of the polyurethane sandwich.

Unfortunately we couldn't get the inventory data for the SuperSap epoxy resin production and therefore we cannot present a complete LCA of the eco-sandwich. Other impacts in Fig. 5 are associated to electricity use for vacuum pump; polyethylene pipes and bags used for resin infusion; scraps waste and final disposal contribute. Landfill was chosen as waste scenario because composite materials cannot be recycled. Another option could be incineration, but in Sicily there are no incinerators and we have discarded this possibility. Fig. 6 shows the eco-sandwich LCA with landfill scenario (horizontal lines) and with incineration scenario (vertical lines). Comparing both scenarios, landfill seems to have minor impacts because it creates less damage on human health and ecosystems. A comparison was made between the polyurethane/glass fibre sandwich reference material and the eco-sandwich using the CML2 software (LCA method CML 2000 v2.0/West Europe, 1995) (Heijungs et al., 1992a,b, Huijbregts et al., 2001; Pré, 2013) with the data presented in Fig. 7 where the reference material is shown as 100% for each of the environmental impact categories. Each impact categories evaluated with CML 2 is in favour of the eco-sandwich. The impact contributions of the polyurethane sandwich are reported in Fig. 8. The major impact contribution is due to the epoxy resin (85%). The same result was found for the eco-sandwich (Fig. 5). The impact increase of the polyurethane sandwich is associated to the use of glass fibre and polyurethane instead than hemp and cork. This is visible by comparing Fig. 5 with Fig. 8. The main drawback of this study is the lack of primary data regarding the SuperSap epoxy resin and the prime LV20 epoxy resin used to make the sandwich panels. Data uncertainty is the main limit of the LCA methodology. Data for both biopolymers and for fossil fuel-based polymers are uncertain and existing databases need to be continually updated and corrected. Data uncertainty also derives by fact that studies are carried out on regional site and the results are to some extent subject to country specific circumstances (e.g., GHG emissions from national power production). On the other hand, the uncertainties related to conclusions can be reduced if several independent analyses for different countries arrive at similar conclusions (Patel et al.).

4. Conclusion

The study presents data results regarding the environmental impact assessment assigned to the production of an eco-sandwich and makes comparison with a traditional polyurethane based sandwich. From the results, it seems that the major contributions to the impact (in both cases, eco-sandwich and traditional sandwich) is due to the use of epoxy resin (environmental impact up to >85%). Data uncertainty is a relevant issue in the LCA methodology. Primary data are useful to reduce data uncertainty. In this contest, the present study could be a useful support because provides new primary data for the cork production and for the eco-sandwich manufacture. There are more aspects to take into account for materials ad process selection such as materials physical performance, materials availability, process efficiency, etc. In the present study, we only evaluate the environmental aspects of materials production. We will discuss the other aspects in a future study.

Moving towards Eco-design, LCA has been recognized as the most comprehensive way of determining the total environmental impact for designing new materials and processes. LCA is a useful tool for choosing clean production processes, avoiding hazardous and toxic materials, maximising the efficiency of the energy used for production and for the product in use and designing for waste management and recycling. Nevertheless, there are still several critical aspects that need to be addressed to future studies.

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