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Environmental implications of the use of agglomerated cork as thermal insulation in buildings

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ABSTRACT

The market for insulation material is playing a crucial role in Europe's energy transformation, due to its influence on energy consumption in buildings. The introduction of renewable materials for thermal insulation is recent, and little is known so far about its environmental implications. This study analyses the environmental performance of a cork insulation board, made of agglomerated cork from forestry cork wastes, by means of cradle-to-gate Life Cycle Assessment methodology. The results indicate that the use of natural insulation materials does not necessarily imply a reduction of environmental impacts due to manufacturing processes with a low technological development. In this case, the most influential stage is the manufacturing stage, in which the board agglomeration and the cork trituration have the highest impacts. The most influential inputs are both the transport used during the life cycle and the large quantities of electricity and diesel in the manufacturing stage. Some strategies have been identified to reduce the environmental impact, such as promote the acquisition of local raw cork to reduce transportation from the manufacturer, improve the efficiency and productivity of manufacturing processes and improve the product design to help increase its market share. Moreover, the inclusion of biogenic carbon contained in forest-based building materials affects the Global Warming Potential results considerably. However, it is very important to consider how this biogenic carbon is calculated and how the product is managed after its lifetime.

1. Introduction

The building sector is one of Europe's main environmental challenges, accounting for more than 40% of the continent's energy consumption and environmental impact (European Commission, 2010). Nevertheless, it is the area with the greatest potential for intervention (Proietti et al., 2013), as improving the sustainability of buildings is crucial to the energy transformation of the European Union (European Commission, 2011a, b). Thermal insulation materials will play an important role in this challenge because of their influence on the energy required to maintain desired interior temperatures and on the environmental impact and embodied energy of the building. Moreover, the introduction of the concept of nearly zero-energy building (NZEB) presented in the European Energy Performance of Buildings Directive 2002/91/EC (EPBD) (European Commission, 2010) and the increased use of passive solutions in buildings will require a greater quantity of insulation in building envelopes. Due to the increased weight of these materials in buildings, their contribution to each building's life cycle environmental impact will be critical (Pargana et al., 2014). Thus, a deep knowledge of the embodied energy and environmental implications of these materials is needed.

Life Cycle Assessment (LCA) methodology (ISO/EN 14040, 2006) has gained increased international acceptance in the building sector. LCA identifies a product's potential environmental impacts throughout its life cycle and also identifies improvement

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Nomenclature

EPD	Environmental Product Declarations
EPBD	Energy Performance of Buildings Directive
XPS	Extruded polystyrene
EPS	Expanded polystyrene
PU	Polyurethane
GW	Glass wool
SW	Stone wool
NZEB	Nearly zero-energy building
CO_2	Carbon dioxide
LCA	Life cycle assessment
FU	Functional unit
EN	European norm
CML	Institute of Environmental Sciences
ADPF	Abiotic depletion potential for fossil resources
ADPE	Abiotic depletion potential for non fossil resources
AP	Acidification potential
EP	Eutrophication potential
GWP	Global warming potential
OLDP	Ozone layer depletion
PCOP	Photochemical oxidation
EE	Embodied energy
CED	Cumulative energy demand

opportunities that may lead to more sustainable solutions (Zabalza Bribián et al., 2009). On the one hand, most studies have focused on building systems, the structure of buildings, and more recently, on green roofs (Cerón-Palma et al., 2013; González-García et al., 2012). On the other hand, LCA has been used to help select materials used in different construction situations (Ferrández-García et al., 2016; Sierra-Pérez et al., 2016). Within the environmental field, there has recently been increased interest in the use of LCA to evaluate insulation materials (Jelle, 2011; Pargana et al., 2014).

The European market for insulation materials is still dominated by two types of products, which are classified according to their chemical or physical structure: mineral or inorganic fibrous materials, namely glass wool (GW) and stone wool (SW), which account for 60% of the market; and organic foamy materials, like expanded polystyrene (EPS), extruded polystyrene (XPS) and polyurethane (PU), which account for approximately 30% of the market (Papadopoulos, 2005; Pfundstein et al., 2012). The LCA studies published in this field have centered on these types of insulation; many companies that manufacture these extended insulation materials have developed their own Environmental Product Declarations (EPD) to communicate the environmental characteristics of their products. Moreover, the rest of the market is composed of other alternative materials, including renewable materials, on which few studies from a life cycle perspective have been published (Ardente et al., 2008; Korjenic et al., 2011; Zampori et al., 2013). The importance of these materials has been increasing due to the strategic minimization of the use of non-renewable materials to reduce the environmental impact of buildings. However, renewable insulation materials still have not undergone sufficient development to be implemented comprehensively in the building sector. Furthermore, the environmental implications of manufacturing these products are still not widely known. Some of these renewable materials have been included in environmental studies, among them: kenaf-fibres, cotton, jute, flax, hemp and cork. Cork is one of the most widespread renewable materials used as thermal insulation, especially in northern Europe (Gil, 2015; Pargana et al., 2014).

The cork material is extracted from the cork oak (*Quercus suber* L.) forests, one of the best examples of balanced conservation and development in the world. The cork oak tree is a long-lived species (250–350 years) with an outer bark, or cork, which is characterized by its elasticity, impermeability and good thermal insulation (Pereira, 2007). Cork extraction is a sustainable process because it does not damage the tree, and following extraction, new bark regrows. This process occurs every 9–14 years, depending on the area, until the tree is approximately 180–200 years old (Pereira and Tomé, 2004). The majority of cork exploitation is concentrated in Portugal and Spain, with these two countries providing 80% of the cork extracted worldwide (161,504 tonnes) (Sierra-Pérez et al., 2015). The environmental importance of cork is the key role that it plays in ecological processes such as water retention, soil conservation, and carbon storage (Rives et al., 2013). Concerning carbon storage, part of the carbon fixed by cork oak trees is transferred to cork products, giving cork products the potential to mitigate climate change by storing carbon for long periods (up until the end-of-life of cork products) (Dias and Arroja, 2014; European Committee for Standardization, 2014a; Gil and Pereira, 2007). Some LCA studies of cork and cork products can be found in the literature, but most of them are related to cork products for the wine sector (Demertzi et al., 2016; Rives et al., 2012b, 2011) and to raw cork extraction (Dias et al., 2014; Rives et al., 2013, 2012a). LCA studies about cork products for the building sector have been published, such as those of flooring (Demertzi et al., 2015b; Jim Bowyer, 2009; Mahalle, 2011) and insulation material (de Brito et al., 2010; Pargana et al., 2014). In studies related to cork as an insulation material, environmental analysis has focused on the comparison with other insulation materials and not in detail on hotspots in product manufacturing. Additionally, the majority of studies have not taken into account the process of releasing biogenic carbon at the end of the cork products' lifetime.

The aim of this cradle-to-gate LCA is to assess in detail the sustainability of cork as an insulation material, quantifying the environmental impact of producing cork insulation boards in Catalonia, Spain. Furthermore, this paper can help to fill a knowledge gap by providing a detailed environmental impact assessment that determines which stages and operations in the production process are most influential. Moreover, some factors, such as source of energy, transport and end-of-life scenarios, have been analysed to determine their influence on the environmental performance of the product.

2. Methods

In this study, an LCA approach is used for the environmental assessment of the manufacturing of white agglomerate cork boards. The LCA of these cork boards has been completed based on the principles described in the ISO 14040 standard (ISO/EN 14040, 2006).

2.1. Goal and scope definition

The main objective of this study is to analyse the environmental impact of the production of cork insulation boards by means of cradle-to-gate LCA methodology, according to the standard for Environmental Product Declaration (EPD) for construction products EN 15804+A1:2014 (European Committee for Standardization, 2014b). The study considers all processes involved in both forest and industrial stages: from the extraction of the cork in the forest to obtaining the final product, taking into consideration raw materials, energy, transports, emissions, etc. The specific objectives are as follows:

- To elaborate an inventory of the materials, machinery and energy consumption in the product life cycle: raw material extraction, transport to the manufacturer and manufacturing.
- To assess the environmental impact of the production of the cork insulation board, identifying the most influential stages and processes.
- To analyse the influence of other energy sources and transport scenarios on the system.
- To analyse the influence of different end-of-life scenarios in the emission of the biogenic carbon stored in the cork boards.

2.2. Product description and functional unit

The product studied is a cork insulation board produced in the largest cork insulation board manufacturing factory in Catalonia, Spain. It consists of white agglomerate cork boards, which are made of forestry cork wastes with the addition of synthetic materials (Polyurethane) to the granules in the manufacturing process. The insulation boards may have different thicknesses, depending on their thermal requirements. The functional unit (FU) used in this LCA study is defined as the mass (kg) of insulation board with an area (A) of 1 m^2 that provides a thermal resistance R-value of 1 m^2 K/W (Ardente et al., 2008; Pargana et al., 2014), as defined in Eq (1).

$$FU = R\lambda\rho A \quad (1)$$

Where R represents the thermal resistance (m^2 K/W), a heating property and a measurement of a temperature difference by which a material resists a heat flow. The greater the R-value is, more insulation the material provides. The factor λ is the thermal conductivity (W/m K), the most important property of any thermal insulation material, i.e., the capacity of a substance to transport thermal energy (Pfundstein et al., 2012). ρ corresponds to the density of the material (kg/m^3), and A is the surface of the façade (m^2). Consequently, the calculations required to decide on the adequate quantity of an insulation material are shown in Table 1.

2.3. System boundaries

The life cycle system is divided into different stages according to EN 15804:2014+A1 (European Committee for Standardization, 2014b) (Fig. 1). The study includes the product stage and all its sub-stages:

A1 – Raw material extraction and processing, processing of secondary material input.
A2 – Transport to the manufacturer
A3 – Manufacturing

Table 1
Properties of the insulation board to fulfill the FU.

	Cork insulation board
Thermal conductivity (λ) (W/m K)	0.042
Density (kg/m^3)	171
Thickness (m)	0.042
Weight (Kg)	7.2

The system considered in this study begins with the extraction of raw cork, considering only operations related to this process. In assessing the extraction, the workers and cork transports within the forest are included, because most operations in this process are entirely manual. Moreover, there are some complementary activities during the period between each stripping that are necessary to facilitate future cork extractions: the scratching stage, the fungicide operation and the shrub clearance and road maintenance. As the raw cork material currently being extracted is the result of the last few decades, it is assumed that similar technology will be used to generate current and future cork.

The next stage is the transport of the cork from the forest to the factory. In this case, 80% of the raw materials are local and the remaining 20% comes from Extremadura, a southwestern region of Spain. All transport to the factory is by road.

The final stage is manufacturing and includes two main substages: cork granulates manufacturing and board manufacturing. The initial materials extracted from the forest are the forestry cork wastes, which do not require that preparation processes be included in the production process. First, the raw cork is received and transferred to the cork trituration process. This operation consists of breaking up the pieces of raw cork into small particles using two types of trituration machines. Then, granulates are classified using densimetric tables that separate the different granulates by density classes. This makes it possible to sort out the heavier particles, which are reprocessed. Moreover, fine particles with dimensions below 0.25 mm are removed as dust throughout the process and may be used as an energy source. This dust represents approximately 50% of the initial raw cork. Granulates of different sizes are stored in silos and are supplied to a dispenser where the agglomeration process involves the blending of the cork with polyurethane. The mixture is placed on a conveyor and is pressed by applying a high temperature; it can then be cut into boards of the desired dimensions. A diesel boiler produces the required heat energy. The wastes generated are introduced again in the agglomeration process and will be used in manufacturing subsequent boards. After the cutting process, the boards are given time for cooling and stabilization. Finally, the boards are packed using polyethylene film and stored until their distribution.

The usage and end-of-life stages have not been included in this study. The usage stage is not included because it is not considered relevant for LCA of thermal insulation materials. In the case of the end-of-life stage, the inventory data from this stage are not available, as the use of these cork insulation boards as an insulation material is very recent.

2.4. Inventory data and impact assessment

A general framework of the stages and operations involved in producing cork insulation boards is based on consultations and visits to the factory and the collection of factory data. This information resulted in a complete questionnaire that included a specific table for each individual operation. Due to the simplicity of the manufacturing process, the reliability and the accuracy of the data reported by the factory manager are high. Furthermore, in the production line only this product is manufactured, so the risk of trade-off data between products is eliminated. Moreover, general data of the factory are also reported, such as the production of the insulation board, water consumption, intermediate transport in the factory, distribution of the auxiliary materials, energy and resources not involved in a specific process, characteristics of all the machinery, etc. These data enable the quantification of global environmental impacts not directly associated with a specific operation. The main flows to produce the established FU of cork insulation board are reported in Table 2. Moreover, it should be

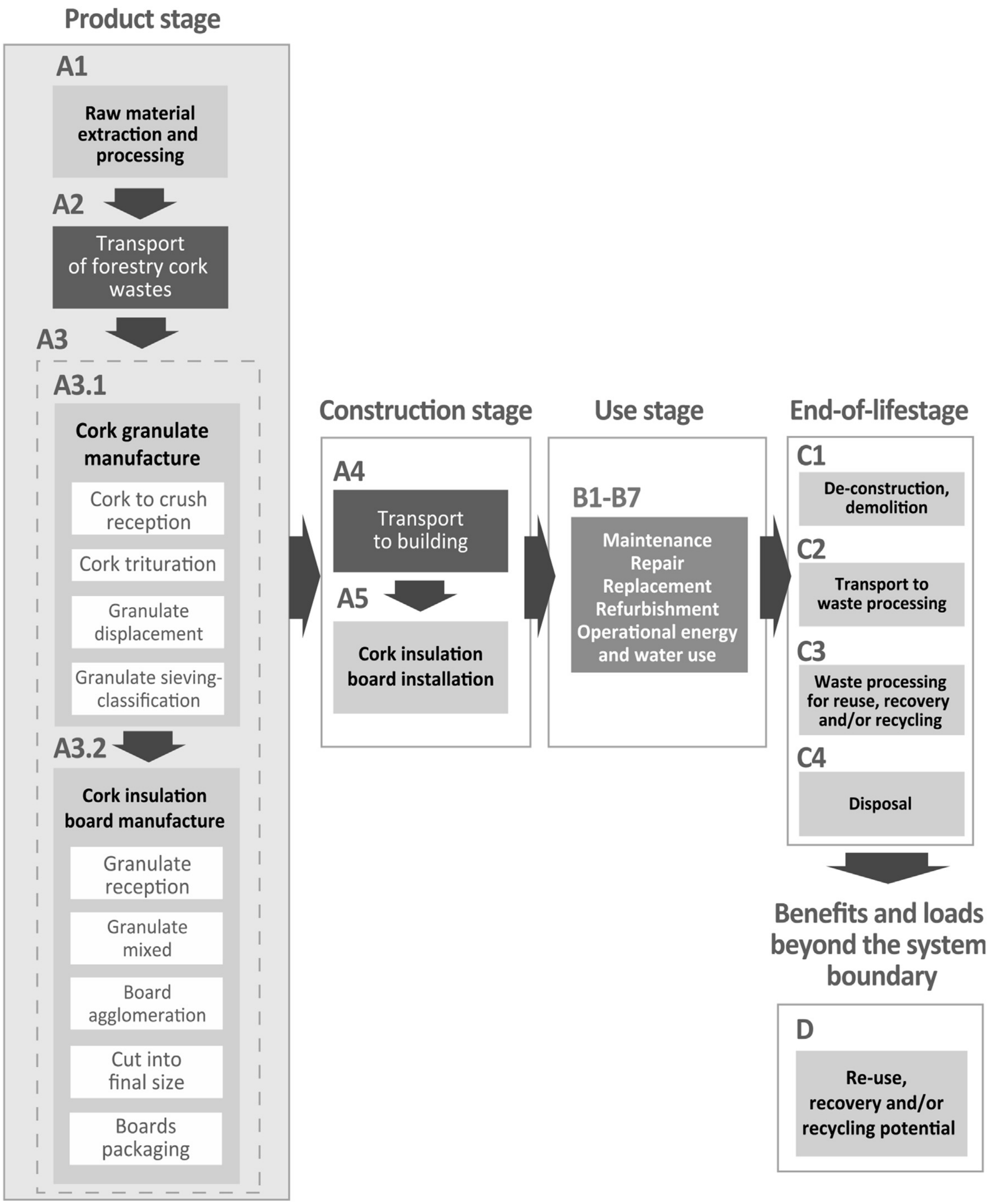

Fig. 1. Diagram of the cork insulation board life cycle based on EN 15408. The study includes A1, A2 and A3 stages.

noted that the specific data for the raw cork extraction is taken from a study by Rives et al. (2012a). These data are included in the inventory because they are assessed with a more updated version of the database used.

Of all of the stages that are included in the LCA methodology (ISO/EN 14040, 2006), only classification and characterization are considered in the impact assessment. According to the European standard that provides the core product category rules for all construction products and services, EN 15804:2014+A1 (European Committee for Standardization, 2014b), the method used is the hierarchical approach of CML 2002 (Guinée et al., 2002), and the mid-point indicators selected are: abiotic depletion potential for non fossil resources (ADPE), abiotic depletion potential for fossil resources (ADPF), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (OLDP) and photochemical oxidation potential (PCOP). Additionally, the embodied energy (EE), or the cumulative energy demand (CED), has been included due to its increasing importance in building energy demand. The software used in the study is Simapro (PRé Consultants, 2010), and the database used to obtain the environmental information related to the processes involved with materials, energy and transport is Ecoinvent 3.1 database

Table 2
Inventory data to produce the FU of cork insulation boards (R = 1 m^2 K/W).

Inputs	Unit	Quantity	Ecoinvent process
A1 – Raw materials extraction			
Materials			
Water	m^3	3.62E–03	tap water production, conventional treatment, Europe without Switzerland
Fungicide (Thiophanate-methyl 45%)	kg	3.03E–03	[thio]carbamate-compound production, RER
Transport			
Workers to stripping	km	1.71E+00	transport, passenger car, large size, diesel, EURO 3, RER
Workers to scratching	km	5.01E–01	transport, passenger car, large size, diesel, EURO 3, RER
Cork to meeting point	km	5.32E+01	transport, tractor and trailer, agricultural, CH
Distribution of auxiliary materials	km	1.00E+02	transport, freight, light commercial vehicle, Europe without Switzerland
Workers to shrub clearance and road maintenance	km	8.63E–01	transport, passenger car, large size, diesel, EURO 3, RER
Forestry tractor	km	1.00E+00	transport, tractor and trailer, agricultural, CH
A2 – Transport to the manufacturer			
From the forest	km	2.40E+02	transport, freight, lorry 16–32 metric ton, EURO3, RER
A3 – Manufacturing			
A3.1 – Granulate manufacture			
Diesel for internal displacements	MJ	7.63E+00	diesel, burned in building machine, GLO
Electricity	kWh	4.40E+00	market for electricity, medium voltage, ES
A3.2 – Board manufacture			
Electricity	kWh	1.45E+00	market for electricity, medium voltage, ES
Diesel boiler	MJ	4.24E+01	heat production, light fuel oil, at boiler 10 kW, non-modulating, Europe without Switzerland
Polyurethane (PU)	kg	1.68E–01	polyurethane production, flexible foam, RER
Transport (PU)	km	2.00E+01	transport, freight, light commercial vehicle, Europe without Switzerland
HPDE	kg	4.55E–02	polyethylene production, high density, granulate, RER

(ecoinvent, 2009). Finally, the allocation procedure is conducted on a mass allocation basis in the raw material extraction stage.

3. Results and discussion

This section presents the LCA results for the production of cork insulation boards. First, the results for the total environmental impact during the life cycle of the product are presented. Next, the relative contribution of each stage to the environmental impact of the manufacturing of the product is described. Finally, sensitivity analyses are carried out by simulating alternative scenarios with the aim to improve the environmental performance of the cork board.

3.1. *Impact assessment of the production of cork insulation boards*

It is observed that different impacts occur during the production of cork insulation boards. The main environmental burdens associated with their production can be found in Table 3. During the production of the required quantity of insulation boards established in the FU, 12.2 kg of CO_2 -eq. is emitted and 211 MJ eq. is used.

If the carbon stored in the forestry products is considered, the GWP results of this forest-based product based will vary considerably. However, the influence of the biogenic carbon contained in the product would be different depending on the different life cycle approaches: cradle-to-gate, cradle-to-grave and cradle-to-cradle (Table 4) (Demertzi et al., 2015a). From a cradle-to-gate approach, to calculate the biogenic carbon content in the final product, the quantity of cork in the insulation board (7.2 kg) is included, so there is a total of 15 kg of biogenic CO_2 (European Committee for Standardization, 2014a). As the end-of-life stage is not taken into account, there is not an emission of biogenic carbon. From a cradle-to-grave approach, in the incineration scenario, there is an emission of the total biogenic carbon content after 50 years, using a correction factor that PAS 2050 (British Standards Institute (BSi), 2011) propose to reflect the number of years of delay in the emissions

Table 3
Environmental impact assessment of the production of the FU of cork insulation boards (R = 1 m^2 K/W).

Stage	Process	ADPE	ADPF	AP	EP	GWP	GWP[a]	OLDP	PCOP	Embodied energy
		kg Sb eq	MJ	kg SO2 – eq	kg PO2- eq	kg CO2 eq	kg CO2 eq	kg CFC-11 eq	kg C2H4 eq	MJ
A1.Raw cork extraction	Total	3.21E–05	3.75E+01	1.21E–02	3.63E–03	2.62E+00	–1.24E+01	4.01E–07	7.95E–04	3.98E+01
A2.Transport to manufacturer	Total	3.40E–06	1.97E+01	6.41E–03	1.57E–03	1.24E+00	1.24E+00	2.28E–07	2.33E–04	2.03E+01
A3 – Manufacturing	Total	2.42E–06	1.28E+02	3.46E–02	9.58E–03	8.33E+00	8.33E+00	1.29E–06	1.49E–03	1.51E+02
A3.1.Granulate manufacture	Total	1.09E–06	4.02E+01	1.77E–02	5.91E–03	2.80E+00	2.80E+00	4.45E–07	6.44E–04	5.66E+01
	Cork reception	3.28E–10	1.68E+00	8.33E–04	1.85E–04	1.08E–01	1.08E–01	2.04E–08	2.00E–05	1.79E+00
	Cork trituration	7.04E–07	2.80E+01	1.25E–02	4.04E–03	1.94E+00	1.94E+00	3.12E–07	4.40E–04	3.87E+01
	Granulate classification	3.84E–07	1.05E+01	4.45E–03	1.68E–03	7.55E–01	7.55E–01	1.13E–07	1.84E–04	1.61E+01
A3.2.Board manufacture	Total	1.34E–06	8.74E+01	1.69E–02	3.68E–03	5.52E+00	5.52E+00	8.41E–07	8.43E–04	9.45E+01
	Granulate reception	2.18E–08	6.00E–01	2.53E–04	9.59E–05	4.29E–02	4.29E–02	6.43E–09	1.05E–05	9.15E–01
	Granulate mixed	2.16E–08	5.95E–01	2.51E–04	9.49E–05	4.25E–02	4.25E–02	6.37E–09	1.04E–05	9.06E–01
	Board agglomeration	1.17E–06	7.96E+01	1.47E–02	2.93E–03	5.11E+00	5.11E+00	7.92E–07	7.36E–04	8.41E+01
	Board cutting	5.95E–08	1.64E+00	6.90E–04	2.61E–04	1.17E–01	1.17E–01	1.75E–08	2.85E–05	2.49E+00
	Packaging	5.88E–08	4.82E+00	9.60E–04	2.75E–04	2.00E–01	2.00E–01	1.68E–08	5.55E–05	5.91E+00
	Storage	4.49E–09	1.23E–01	5.21E–05	1.97E–05	8.83E–03	8.83E–03	1.32E–09	2.15E–06	1.88E–01
Total		3.79E–05	1.85E+02	5.32E–02	1.48E–02	1.22E+01	–2.86E+00	1.91E–06	2.52E–03	2.11E+02

[a] Includes the biogenic carbon contained in FU.

Table 4
Quantities of biogenic carbon emitted and stored by the cork insulation board for the end-of-life scenarios included in the study.

	Cradle-to-gate	Cradle-to-grave		Cradle-to-cradle	
	Not including end-of-life	Incineration	Landfill	Recycling	
Manufacturing emissions (Kg of CO_2 −eq)	1.22E+01	1.22E+01	1.22E+01	First product	1.22E+01
				Second product	9.58E+00
Biogenic carbon emitted (Kg of CO_2 −eq)	–	7.50E+00	1.18E−01	First product	–
				Second product	–
Biogenic carbon stored (Kg of CO_2 −eq)	1.50E+01	7.50E+00	1.48E+01	First product	1.50E+01
				Second product	1.50E+01
Balance (Kg of CO2 −eq)	**−2.86E+00**	**4.70E+00**	**−2.68E+00**	**First product**	**−2.86E+00**
				Second product	**−5.42E+00**

being released. In the incineration, the biogenic carbon is emitted to the atmosphere, but the manufacturing process can use the thermal energy obtained in this combustion. In the case of the landfilling scenario, 98% of biogenic carbon remains permanently contained in the product and 2% is emitted at a constant rate over 20 years. From a cradle-to-cradle approach, recycling of the material to manufacture another cork insulation board with the same lifespan has been proposed. On the one hand, in the manufacturing of the second product the raw cork extraction stage has not been taken into account because of the raw materials proceeds from the first product. On the other hand, all the biogenic carbon is transferred to the second product because the cork properties are unaffected in the white agglomerate manufacture. The first product is crushed and introduced to the agglomerate process, and the material losses during these processes are dismissed. In this case, as the sum of the lifetime of the two products is 100 years, the PAS 2050 consider the biogenic carbon to be permanently stored. Table 3 has an additional column with the GWP category, including the biogenic carbon from a cradle-to-site approach, which is consistent with the system boundaries. However, Table 4 also includes the calculation of the biogenic carbon emitted and stored for the three alternatives to end-of-life, which will be discussed in following sections.

Fig. 2 shows the distribution of the impacts for cork insulation board according to each stage in the production process. It can be observed that the manufacturing stage (A3) represents the most influential stage for the majority of the environmental impact categories, accounting for more than 60% of the total environmental impact, except for the ADPE. The manufacturing stage (A3) includes the granulate manufacture (A3.1) and the board manufacture (A3.2) sub-stages. On the one hand, the board manufacture has the greatest impacts in most of the impact categories, including the embodied energy in the final product. On the other hand, the granulate manufacture is the most influential stage for the EP, representing 36% of the total. In GWP terms, the board manufacture (A3.2) represents more than 50% of total impact, and the granulate manufacture (A3.1) and the raw cork extraction (A1) have similar impact on the environmental performance of the product, accounting for 20%. Moreover, it can be noted that for the impact category ADPE, the raw cork extraction stage reaches more than 80% of total impact. This is due to the fungicide operation and the use of Thiophanate-methyl 45%. These stages will be described in detail in the following sections. Regarding the transport-to-manufacturer stage (A2), it can be seen that it is the least influential stage for the majority of the environmental impact categories, between 8 and 14% of total impact.

Table 5 shows the most influential inputs in the product life cycle. It can be noted that most of the environmental impacts are caused by the use of diesel; this energy source is used in the forklift truck for the internal displacements, but the boiler causes the higher impacts in the generation of high temperatures required for the agglomeration. Moreover, the influence of both the large quantities of electricity in the manufacturing and the transport used during the life cycle (in the raw cork extraction and transport to the manufacturer) are significant. At the end of this paper, improvement analyses of these aspects will be carried out to study how this aspect could change the absolute and relative results. The use of polyurethane as agglutinant material in this composite agglomerate board does not result in large impacts, but it could be avoided by using a less impactful material.

3.2. Impact assessment of the production of cork insulation board by stages

In this section, the relative results of the production stages are analysed to facilitate comparative analysis between operations.

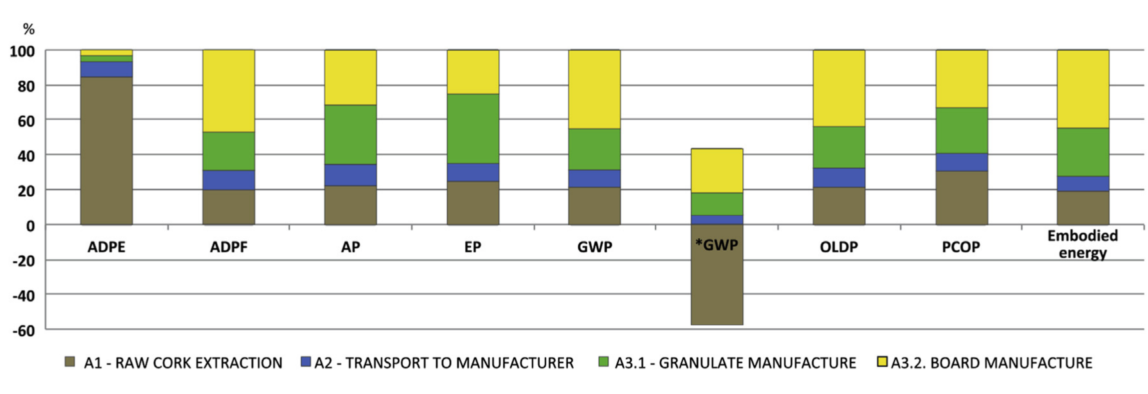

Fig. 2. Environmental impacts assessment of cork insulation boards by production stages.

Table 5
Relation between the environmental impacts of the main inputs and the total impacts of the cork insulation board.

		ADPE	ADPF	AP	EP	GWP	OLDP	PCOP	Embodied energy
Total diesel	Manufacturing	0.0%	37.7%	26.0%	13.6%	37.2%	44.2%	23.1%	33.5%
Total Electricicty	Manufacturing	3.9%	21.8%	31.9%	43.5%	23.6%	22.5%	27.9%	28.1%
Total Transport	Forest	56.7%	20.0%	22.4%	23.6%	21.3%	20.5%	31.0%	18.5%
	To manufacturer	9.0%	10.7%	12.1%	10.6%	10.1%	11.9%	9.3%	9.6%
Total PU	Manufacturing	2.5%	7.9%	6.6%	7.6%	6.8%	0.5%	7.0%	8.3%

<10% 10-30% >30%

3.2.1. Extraction of the raw cork: impact assessment

This stage has already been evaluated by Rives et al. (Rives et al., 2012a), and as noted above, the inventory data for the present study are taken from this study. However, the present study has been performed using a more updated environmental Ecoinvent 3.1 database (ecoinvent, 2009), and some differences have been identified between the two studies. The most influential difference is the update of the environmental information for Thiophanate-methyl 45%. In the newest Ecoinvent version, this process has increased the environmental values by more than 30% in most of the environmental categories. Moreover, due to the greater variety of types of transport in the updated environmental database, more suitable and reliable processes have been used. In summary, the impact value in GWP terms in Rives et al. (Rives et al., 2012a). was 0.191 kg CO_2 -eq per kg of raw cork, in contrast with the results in this study: 0.081 kg CO_2 –eq per kg of raw cork.

The raw cork extraction stage has three operations with significant impacts: the workers' transport, the cork transport to the meeting point and the fungicide operation (Fig. 3). As noted in Table 5, the transport during the forest stage has great importance in all impact categories and accounts for more than 15% of total impacts, with more than 50% in ADPE. The transport of cork after being extracted involves more than 30% in AP, EP and PCOP. Meanwhile, the fungicide operation, as mentioned above, has a great influence in the ADPE due to the use of Thiophanate-methyl 45%. Finally, the shrub clearance and road maintenance represents approximately 10% of raw cork extraction impacts for all categories.

3.2.2. Transport to manufacturer: impact assessment

As cited above, the transport to manufacturer is the least influential stage for the majority of the environmental impact categories (Fig. 2). This stage has different factors to consider; among the most important is the distance of transport. In the case of cork, this factor is more important due to the geographical concentration of the oak cork forest. In this case, the cork boards are manufactured in a factory from Catalonia, and most of the raw material is from a local forest, which reduces significantly the influence of this stage. Despite of the low productivity of the Catalan forest, the availability of forest waste is great because few companies in the Catalan cork sector demand it.

3.2.3. Granulate manufacture stage: impact assessment

This is the first sub-stage (A3.1) of the manufacturing stage (A3), and Fig. 4 shows the relative contribution of each operation to the environmental impact of the granulate manufacturing. The most influential operation for all the impact categories is the cork trituration, representing more than 60% of total impacts in this stage

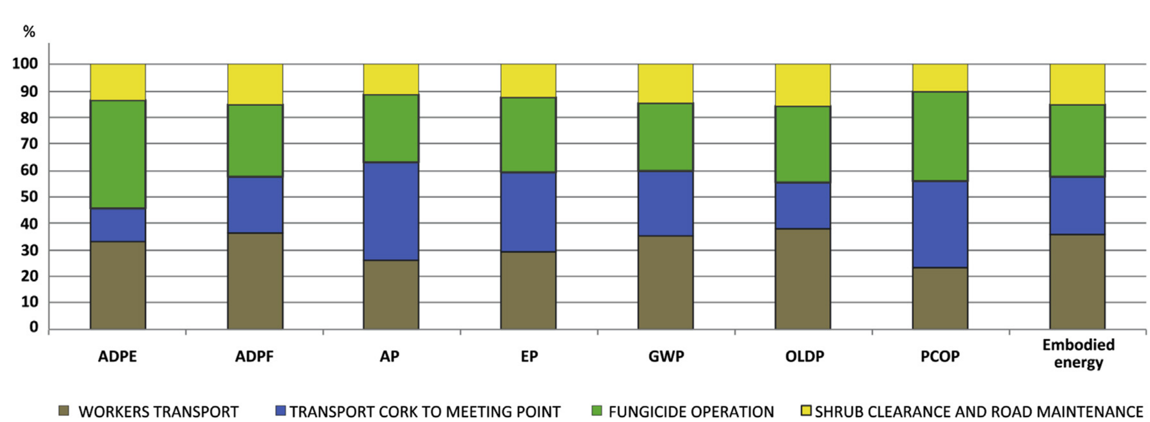

Fig. 3. Environmental impact of the raw cork extraction (A1) by production processes.

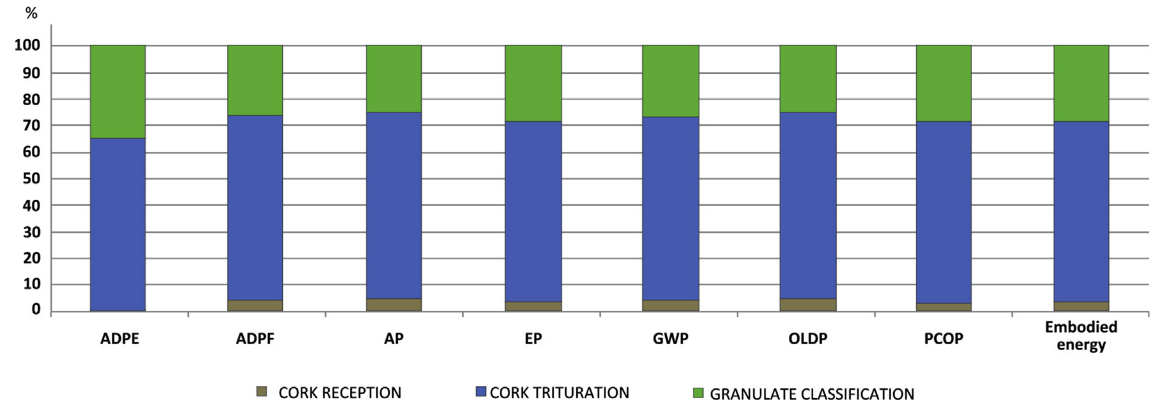

Fig. 4. Environmental impact of the granulate manufacture (A3.1) by production processes.

and between 15 and 27% of total impacts, unless for ADPE. This stage also includes the classification and sieving of granulates, which also contributes considerably to the relative impacts of the granulate manufacture stage: between 25 and 35%.

The environmental impacts of electricity consumption in this stage represent between 75 and 90% of the total impact of this stage. For that reason, the influence of the source of this electricity will be assessed in the following sections. Moreover, this stage generates most of the cork waste in the whole manufacturing process. Due to the low quality of the raw material, the trituration process rejects more than 50% of the initial raw cork, mainly as dust of cork. In this factory, this dust is not used as biomass to generate energy.

3.2.4. Board manufacture stage: impact assessment

The stage includes the conformation of the insulation boards, accounting for the largest environmental impacts in the majority of the categories (Fig. 5). With the exception of ADPE, all impact categories represent more than 20% of global impacts, and in the case of ADPF, GWP, OLDP and Embodied Energy, represent more than 40%.

The energy required to reach the high temperature of agglomeration is obtained by a diesel boiler, which accounts for the highest impacts of this stage. It represents more than 50% in relative terms and approximately 30% in absolute terms, for ADPF, GWP, OLDP and Embodied Energy. For AP and PCOP, this operation represents more than 15% of global impact. In addition to the diesel boiler for the thermal energy, significant electricity consumption is needed for the rest of operations in this stage. As mentioned above, the use of agglutinant to manufacture the composite agglomerate of cork implies a generation of environmental impacts. In the present study, the use of PU as agglutinant represents relative impacts of between 0.5 and 8.3% (Table 5), depending on the impact category, with GWP being the most influential impact category OLDP being the least influential. The remaining operations (board cutting, packaging and storage) are below 3% of total impacts for all the impact categories. The operations included in this stage have a high efficiency and do not generate waste. The waste generated in the board cutting operation is reintroduced into the silo where the mixing takes place.

3.3. Comparison with previous studies

As mentioned above, the environmental performance of cork as an insulation material has not been widely studied until now. Only a few studies have reported information about the environmental implications of the use of cork insulation boards. On the one hand, the study of Zabalza Bribián et al. (2011) presents a comparison among the most common insulation materials, including cork. A direct comparison between that study and the present study is not very feasible due to the use of different methodologies. However, if the Bribian results are converted to the FU used in this study, this reveals a great disparity in the results, both in GWP and Embodied Energy (Table 6). On the other hand, the study of Pargana et al. (2014) follows the same methodology of the present study, following the standard EN 15804 and the CML method.

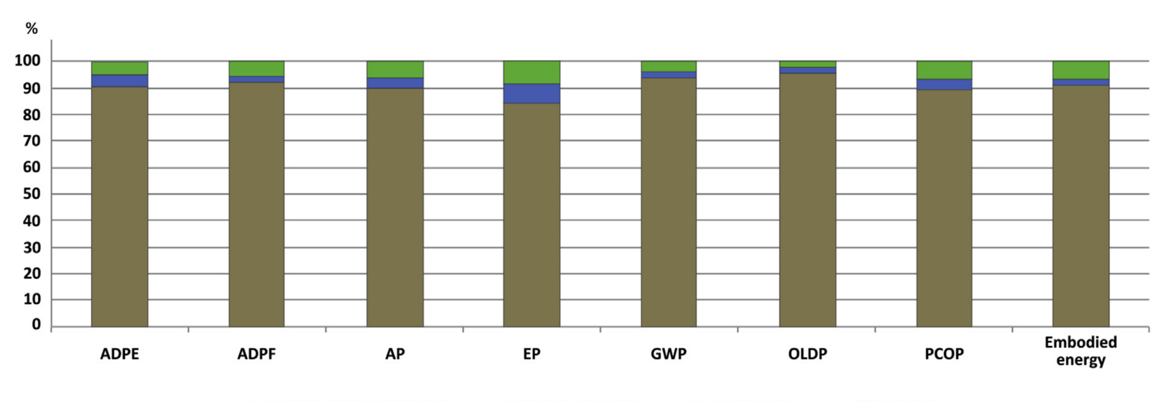

Fig. 5. Environmental impact of the board manufacture (A3.2) by production processes.

Table 6
Comparison of the results with previous studies including cork and the most common insulation materials.

Insulation material	Ref.	ADPE	ADPF	AP	EP	GWP	GWP[a]	OLDP	PCOP	Embodied energy
		kg Sb eq	MJ	kg SO_2 − eq	kg PO_2- eq	kg CO_2 eq	kg CO_2 eq	kg CFC-11 eq	kg C_2H_4 eq	MJ
Cork	(1)	–	–	–	–	5.93E00	–	–	–	3.78E+02
	(2)	1.30E−02	–	3.60E−02	1.60E−02	1.61E00	–	1.11E−07	2.55E−03	3.39E+02
	(3)	3.79E−05	1.85E+02	5.32E−02	1.48E−02	1.22E+01	−2.86E00	1.91E−06	2.52E−03	2.11E+02
EPS	(1)	–	–	–	–	8.25E00	–	–	–	1.18E+02
	(2)	3.5E−02	–	1.1E−02	1.35E−03	3.25E00	–	9.25E−08	5.83E−03	7.44E+01
XPS	(1)	–	–	–	–	–	–	–	–	–
	(2)	4.7E−02	–	1.7 E−02	1.83E−03	5.21E00	–	4.30E−08	1.3 E−02	9.81E+01
PU	(1)	–	–	–	–	6.51E00	–	–	–	9.9E+01
	(2)	3.5 E−02	–	1.3 E−02	1.56E−03	3.33E00	–	8.23E−08	1.17E−03	8.59E+01
SW	(1)	–	–	–	–	3.6E00	–	–	–	6.33E+01
	(2)	–	–	–	–	–	–	–	–	–

(1) (Zabalza Bribián et al., 2011).
(2) (Pargana et al., 2014).
(3) Present study.
[a] Included the biogenic carbon content in FU.

However, the results are quite different, especially in GWP, OLDP and Embodied Energy (Table 6). The main reason is that Pargana uses ICB composed of expanded cork, while this study uses white agglomerated cork. The composite agglomerated board needs more quantity of raw cork to manufacture the same FU than does the expanded cork board, so the kg CO_2 -eq. emitted is higher. However, in contrast, the manufacture of the expanded cork board is more energy intensive because the expansion process needs more thermal energy than the agglomeration process. Moreover, neither of the two previous studies takes into account the biogenic carbon of the board so it is not possible to fully compare the results obtained.

Finally, Table 6 compares different cork boards with the most common insulation materials used in Europe: expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PU) and Stone wool (SW) (Ardente et al., 2008; Papadopoulos, 2005). As mentioned above, the cork can help to mitigate GWP due to its biogenic carbon storage, unless incineration in the end-of-life scenario is included (Table 4). The quantity of CO_2 -eq emitted during the incineration results is similar to the rest of the insulation materials evaluated. The cork insulation board discussed in this study implies higher impacts than the rest of the insulation materials for the majority of the impact categories, so the use of natural insulation materials does not necessarily imply a reduction of environmental impacts. The main reason, as discussed in the following section, is the low technological development of the cork board insulation manufacturing process. Therefore, it is necessary to implement improvements at different stages of the board's life cycle, to further cork's advantages in mitigating GWP.

3.4. Improvement analysis

In previous sections, it has been noted that the most influential inputs in the life cycle of cork products are transport and energy consumption (electricity and diesel). In this section, different scenarios for transport and energy sources are analysed to improve the environmental performance of the insulation board as well as to increase the efficiency of the manufacturing process.

3.4.1. Influence of the transport on the system

Throughout the entire production process, transport inputs can be classified as either transport in the raw cork extraction stage or transport to the manufacturer. Both have important influences on emissions and energy consumption and depend on different factors, which are discussed below. Regarding transport during the raw cork extraction, due to the irregular orographic conditions of the oak cork forests in Catalonia, the use of all terrain vehicles is required. These vehicles are used to transport workers for stripping, scratching and shrub clearance and road maintenance. The environmental impacts of these vehicles are important but their substitution with a more sustainable vehicle, without compromising process efficiency, is not possible.

Moreover, regarding the impact of transport to manufacturer, the factor with more influence on total emissions is the distance from forest to factory. In this case, most of the raw cork comes from local forest but 20% of the initial raw cork still has to travel 1100 km from southern Spain. This is because of insufficient cork production in Catalonia, as Catalan cork oak forests are not fully used at present; it is estimated that 50% of them are not managed in any way (Tusell and Garcia, 2008). If the exploitation of these forests begins, cork extraction in Catalonia could be doubled, and this dependence on southern Spanish forests would decrease. A future scenario of 100% local raw cork is analysed and presented in the Table 7. All the impact categories present important improvements, between 6 and 10% in absolute values. In addition to the environmental improvements, use of local products could support the development of rural areas where cork is the primary economic activity. Moreover, if transport of the raw cork to the manufacturer was in a more efficient vehicle (for instance in a lorry type EURO5), the global results only decrease in 1% in GWP terms. This underscores the importance of the distance travelled by the raw material and therefore the value of promoting the consumption of local raw materials.

Table 7
Improvements in the environmental impact and energy consumption for the proposed scenarios.

	ADPE	ADPF	AP	EP	GWP	OLDP	PCOP	Embodied energy
100% local raw cork	−8.0%	−9.0%	−7.4%	−9.1%	−8.6%	−10.0%	−6.1%	−8.1%
Decarbonisation scenario	−9.8%	−25.8%	−29.4%	−54.9%	−30.1%	−22.1%	−23.7%	−29.6%
Diesel substitution	0.0%	−28.7%	39.3%	42.0%	−27.8%	−37.1%	24.0%	−25.3%
Improvements	−17.79%	−63.54%	2.47%	−21.98%	−66.43%	−69.15%	−5.86%	−62.96%

3.4.2. Influence of the type of electricity on the system

The manufacturing of cork insulation boards requires high electricity consumption, mainly for granulate production and in the agglomeration process. The electricity mix used in Spain has a carbon intensity of 0.48 kg of CO_2 per kWh the acquisition date of these data is 2008 (ecoinvent, 2009), due to the use of fossil sources of energy as coal and fuel. In the medium term, the European Commission has proposed an energy decarbonisation roadmap based on switching to renewable and nuclear energy sources, an increasing share of gas in fossil fuel generation and significant penetration of carbon capture and storage (CCS) (European Commission, 2011b). In this section, a future scenario is simulated to analyse the influence of the decarbonisation electricity scenario in the environmental performance of the product (Table 7). Some studies have already analysed the influence of lower-carbon scenarios in the environmental performance of the Spanish electricity mix (Foidart et al., 2010; Spork et al., 2014). The new scenario represents a Spanish electricity mix aligned with this European roadmap for 2050 with an average distribution within the proposed range. It includes 48.5% from renewable energy sources, 21.5% from natural gas, 14.3% from oil, 9.7% from nuclear and 5.9% from solid fuels, with a carbon intensity of 0.10 kg of CO_2 per kWh (European Commission, 2011b). The environmental improvements are significant in all the impact categories (Table 7), especially in EP (−54.9%), GWP (−30.1%) and Embodied Energy (−29.6%). This scenario represents an avoided emission of 3.7 kg of CO_2 eq. and an avoided energy consumption of 62.5 MJ per FU. This demonstrates the importance of energy choices in analysing this product. To implement this strategy in the short term, the factory could install renewable energy systems such as photovoltaic panels or biomass cogeneration.

3.4.3. Influence of source of energy used in the agglomeration process

As noted above, the use of diesel in the manufacturing process plays a significant role in the global impact of this product, especially in the case of the diesel boiler for the board agglomeration. In this section, the influence of the use of alternative sources of energy is analysed (Table 7). In the proposed scenario, the dust cork, the waste resulting from the manufacturing process, is used as biomass. As the calorific value of the cork (20.6 MJ/kg) (Mediavilla et al., 2009) is lower than diesel (46 MJ/kg), the quantity of cork required to obtain the MJ needed for the agglomeration will be higher: 3 kg of cork instead of 1.34 kg of diesel. The calculations for the air emissions in the combustion for cork are based on emission factors from IPCC (2006) (IPCC, 2006) and EEA (2013) (EEA, 2013). As shown in Table 7, the improvements are significant in most of the categories, mainly in ADPF, GWP and OLDP. It is also important to note the major improvement in the Embodied Energy of the product, which consumes 28% less energy in the manufacturing process. This is because the input related to this energy does not need to be taken into account again in the inventory as it proceeds from the initial raw cork and has already been included in the initial inventory. Moreover, in some impact categories, the results are worse than those in the actual scenario, especially in EP and AP. This is due to the substances emitted in the cork combustion, such as nitrogen oxides, ammonia and dinitrogen monoxide. Cork is not the best fuel biomass for all impact categories, although it represents a use of an existing raw material in the factory. However, this result could be balanced by implementing some of the other environmental improvements proposed.

3.4.4. Summary of improvements and future challenges

Table 7 also includes the cumulative improvements from all scenarios because all improvements are complementary to each other. It should be noted that the decreases in all impact categories are drastic; e.g., the reduction in ADPF, GWP, OLDP and Embodied Energy are higher than 60% and the reduction in the ADPE and PCOP reach 17% and 5%, respectively. In the case of AP, due to the poorer results in the substitution of diesel by cork dust, the final results represent an increase in its value. In summary, the improvements will result in a less intensive product, both in greenhouse gas emissions (4.85 kg of CO_2 -eq. per FU) and in energy consumption (91 MJ per FU).

In addition to the proposed improvements, the cork insulation board manufacturing sector needs to implement an overall improvement strategy and a series of eco-design strategies throughout the product's life cycle and manufacturing process. On the one hand, the sector has identified the need to improve the efficiency and productivity of the cork board manufacturing process. On the other hand, it must increase the competitiveness of its product, improving its design to suit market needs and increase market share.

Renewable materials, and especially cork, represent a sector with great potential for intervention. Accounting for the biogenic carbon contained in cork can improve the environmental performance of buildings, but it is very important to analyse how this biogenic carbon is calculated and how the product is managed after its lifetime. The use of forest-based building materials will support an increase in the sustainability in the building sector; as discussed above, it is crucial to the transformation of the UE energetic framework.

4. Conclusions

- The cork board manufacturing stage, including granulate manufacturing and board agglomeration, is the most impactful stage for the majority of environmental impact categories. The most influential factors in the product life cycle are the transport used during the life cycle (in the raw cork extraction and the transport to the manufacturer) and the large quantities of electricity and diesel in the manufacturing stage.
- The cork insulation board discussed in this study implies higher impacts than the rest of the most common insulation materials for the majority of the impact categories, so the use of natural insulation materials does not necessarily imply a reduction of environmental impacts.
- Some eco-design strategies should be implemented at different stages of the life cycle and the manufacturing process. The manufacturing processes should be made more efficient and productive to increase the competitiveness of the product. The product design should be improved to help increase its market share. Moreover, it has to promote the acquisition of local raw cork to reduce the transport distance to the manufacturer
- The inclusion of biogenic carbon in the environmental assessment of forest-based building materials improves the GWP results considerably. However, it is very important to analyse how this biogenic carbon is calculated and how the product is managed after its lifetime. For the majority of the end-of-life scenarios proposed in the study, the biogenic carbon helps to mitigate GWP caused by the boards' manufacturing.

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