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# Life cycle assessment of innovative insulation panels based on eucalyptus bark fibers

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ABSTRACT

This paper reports on the environmental issues associated with the manufacturing of a new insulation material (panel) produced with fibers from Eucalyptus bark. The analyses consider four types of eucalyptus bark panels with different bulk densities (25, 50, 75 and 100 $kg/m^3$). For each type of panel, the environmental impact assessment is performed using Life Cycle Assessment (LCA) methodology and considering system boundaries from cradle to gate. Major environmental impacts were associated to the panel with a density of 100 $kg/m^3$, due to the higher mass required for the same functional unit ($R = 1$ $m^2K/W$). The panel manufacturing, forest management and biomass transport were the stages with the highest significance, mainly due to: the contribution of the synthetic fiber used for binding the bark-derived fibers, intensive use of agrochemicals in forest management and long traveled distances for biomass transportation. Furthermore, the eucalyptus bark panels with densities of 25 and 50 $kg/m^3$ shown the lower embodied energy and carbon emissions than traditional insulation materials (expanded polyurethane, polystyrene, glass fibers and glass wool). Therefore, it could be an attractive insulation material for a more sustainable building sector.



## 1. Introduction

In recent years, the world energy demand has increased significantly; leading to a proportional increment in the environmental pollution and greenhouse gases emissions (GHG) (IEA and UNEP, 2018). The building sector plays an essential role in the global energy scenario as it consumes approximately 30–40% of the primary energy and, also it accounts for one-third of global greenhouse gases emissions (Evin and Ucar, 2019; Papadopoulos et al., 2015; Yılmaz et al., 2019). In the Chilean context, the residential sector consumes about 21% of the total final energy and contributed nearly of 3.8% to the total greenhouse gases emissions (Ministerio de Energía, 2016; MMA, 2018). These impacts are associated to the inefficient household heating technologies (wood-based), as well as, to the lack of efficient thermal insulations in the buildings. Accordingly, several initiatives and regulations related to the building and construction sectors have been included in public policies, at national and regional levels (CDT, 2015; MINVU, 2013). Most of these legal instruments are focussed on reducing the environmental impacts during construction and operation phases, by the efficient use of resources (energy and water) and including more sustainable materials for buildings. Indeed, the development of sustainable thermal insulating materials is a challenge for the industry and for the science en route to achieve high environmental standards (Torres-rivas et al., 2018). In this scenario, natural fibers have emerged as a promising alternative due to the wide variety of fiber sources, high availability as a by-product or residue, low mass density, good acoustic and thermal insulation properties, as well as, to its low environmental impacts as compared to synthetic fibers (Ardente et al., 2008; Arrigoni et al., 2017; Asdrubali et al., 2015; Buratti et al., 2018; Cetiner and Shea, 2018; Liu et al., 2017; Schiavoni et al., 2016). In this sense, many studies have demonstrated the technical and environmental competitivity of several natural fibers: hemp (Florea and Manea, 2019; Ricciardi et al., 2014), kenaf (Ardente et al., 2008; Korjenic and

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Petránek, 2011; Kyma and Sjo, 2008), cotton stalks (Asdrubali et al., 2015; Binici et al., 2014), corn straws (Pinto et al., 2011; Rojas et al., 2019), rice husk (Buratti et al., 2018), wood waste (Cetiner and Shea, 2018); for building insulation applications. In a recent study (Fuentealba et al., 2016), have studied the thermal properties of insulation panels produced from forest by-products, specifically Eucalyptus bark. The experimental results showed that thermal conductivity was between 0.042 and 0.049 W/mK for panel densities varying from 25 to 100 kg/m$^3$. These results are comparable to many common commercialized synthetic fibers.

In Chile, *Eucalyptus nitens* and *Eucalyptus globulus* plantations represent 35% of total hectares covered by forestry plantations (2,414,208 ha), which implies a volume of harvested biomass of approximately 12,000 thousands of m$^3$ (INFOR, 2017), estimating approximately 1,200 thousands of m$^3$ of bark. Most of this by-product is commonly sold at low costs (3–5.6 USD/m$^3$) (INFOR, 2018) to local pulp and paper industries for heat and power production. However (Fuentealba et al., 2016), have demonstrated that Eucalyptus bark has adequate morphology and physical properties to be used as innovative insulation material. Thus, using Eucalyptus bark as insulation material is a very attractive alternative to add-value to this forest by-product and to give an ecological solution for the building sector. Nevertheless, there are no studies reporting on the environmental impacts associated with the manufacture of insulation panels using Eucalyptus bark. Therefore, the main objective of this study is to identify, -from a Life Cycle assessment perspective-, the environmental significance of the stages involved in the manufacturing of eucalyptus bark panels. Moreover, a comparison framework between bark-based panels, conventional and unconventional insulation materials reported in the literature, is established by emphasizing in their impacts on equivalent carbon emissions and embodied energy.

## 2. Materials and methods

The environmental impacts related to the manufacturing of an insulation biomaterial obtained from Eucalyptus bark fibers, are assessed based on Life Cycle Assessment (LCA) methodology and according to the guidelines of the international standard organization (ISO) (ISO 14040, 2006). The LCA involves four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. The phases involved in this analysis are described below:

### 2.1. Goal and scope definition

The goal of the analysis is the environmental evaluation of the manufacturing of thermal insulation panels using Eucalyptus bark fibers. The analysis follows the concept cradle-to-gate and, the results are compared to the main insulation materials used in the Chilean building sector. Moreover, a comparative analysis between eucalyptus bark panels with different densities was carried out, in order to choose the alternative with higher environmental benefits. In this case, four alternative panels corresponding to 20, 50, 75 and 100 kg/m$^3$ of densities are compared.

The studied system includes the production of biomass (eucalyptus plantations management), wood chip process, panel manufacturing and transport stages (biomass, agrochemicals and additives). The production of fossil fuels (forest machinery, biomass transport and panel manufacturing), agrochemicals (fertilizers and pesticides) and additives (synthetic fibers, antifungal and flame retardant) used in the whole production chain, are also considered.

The electricity demand for wood chips processing and panel manufacturing is taken into account using the technological details of the Chilean national electric system (SEN). For 2018, the Chilean electricity matrix was mainly based on coal-fueled thermo-power systems (43%), followed by hydropower (26%) and natural gas (14%). The rest of the generation capacity came from solar photovoltaic (8%) and wind turbines (6%) (CNE, 2018).

#### 2.1.1. Functional unit

The functional unit (f.u.) is the mass (kg) of insulation material delivering 1 m$^2$K/W of thermal resistance R. This f.u. was chosen according to the Council for European Producers of Materials for Construction (Ardente et al., 2008; Buratti et al., 2018; CEPMC, 2000) and it is calculated by the following expression (Eq. (1)).

$$f.u. = R.\lambda.\rho.A \tag{1}$$

Where f.u is the mass (kg), R corresponds to thermal resistance equal one m$^2$K/W, λ and ρ represent the panel thermal conductivity (W/mK) and density (kg/m$^3$), respectively. The term A is the area of the panel, which is equal to 1 m$^2$. The properties λ, ρ and f.u for each eucalyptus bark panel are presented in Table 1.

#### 2.1.2. System boundaries

The system boundaries involved the eucalyptus bark extraction (forest management and wood chip process), biomass transport to the panels production facility and the manufacturing of the panels until they are ready for distribution (-at the factory gate). These stages were considered according to the well-known cradle-to-gate approach. The stages related to the installation and maintenance of the panels, as well as, the disposal at the end of their life (grave), were not considered due to it is a new insulation material and there are no data available for these stages (Buratti et al., 2018; Ricciardi et al., 2014). The cradle-to-gate system boundaries of eucalyptus bark panel chain are shown in Fig. 1.

The biomass supply chain included forest management, transport, wood chip process and panel manufacturing.

*2.1.2.1. Forest management.* The forest management data was based on real practices carried out in Chile. In this stage, a eucalyptus short-rotation plantation (12 years) was considered as reference (Morales et al., 2015). This phase involved the plantations stamp establishment, harvesting, as well as, infrastructure. Firstly, the site preparation is carried out by means of land cleaning, ripping and weed control with herbicides (3.5 lts glyphosate/ha), followed by stamp planting. This last phase includes the weed control (2.0 lts glyphosate/ha) and fertilization (32 kg ternary fertilizer/ha). Afterward, the harvesting phase involves three cutting cycles every four years, which needs for agrochemicals and fossil fuels. The same doses of fertilizer (100 kg diammonium phosphate/ha) and herbicides (2 lts glyphosate/ha) are applied for each cutting cycle. Finally, the eucalyptus is harvested after 12 years, considering an average biomass yield of 18.8 m$^3$/ha.yr.

Besides, the infrastructure includes the roads and building maintenance; being the fossil fuel consumption the main requirement in this stage. More information about the inventory of forest scenario can be found in (Morales et al., 2015).

*2.1.2.2. Wood chipping process.* The existing stationary wood chipping stations installed in the Biobío region were taken as reference in this paper. The wood chip yield was assumed at 35% (m$^3$chips/m$^3$logs) and it included the *Eucalyptus globulus* logs reception, debarking, chipping and chips classification stages. The chips are the primary products; meanwhile, the eucalyptus bark and fine biomass (sawdust) are considered as by-products, which are used for energy applications. The energy resources (electricity and fossil fuel) are the main requirement in this stage. In this case, the average electricity demand (21 kWh) and fossil fuels

**Table 1**
Characteristic properties of eucalyptus bark panel.

| Properties | Unit | Value | | | |
|---|---|---|---|---|---|
| Bulk density, ρ | $kg/m^3$ | 25 | 50 | 75 | 100 |
| Thermal conductivity, λ | W/m.K | 0.045 | 0.046 | 0.048 | 0.049 |
| Thermal diffusivity, $10^{-7}$ | $m^2/s$ | 7.9 | 4.4 | 3.0 | 2.4 |
| Specific heat capacity | J/kg.K | 2198 | | | |
| Thickness | mm | 50 | 50 | 50 | 50 |
| Thermal resistance, R100 (NCh 853–2007) | $m^2$.K/W | 111 | 109 | 104 | 102 |
| **Functional unit (f.u.)** | **kg** | **1.125** | **2.3** | **3.6** | **4.9** |

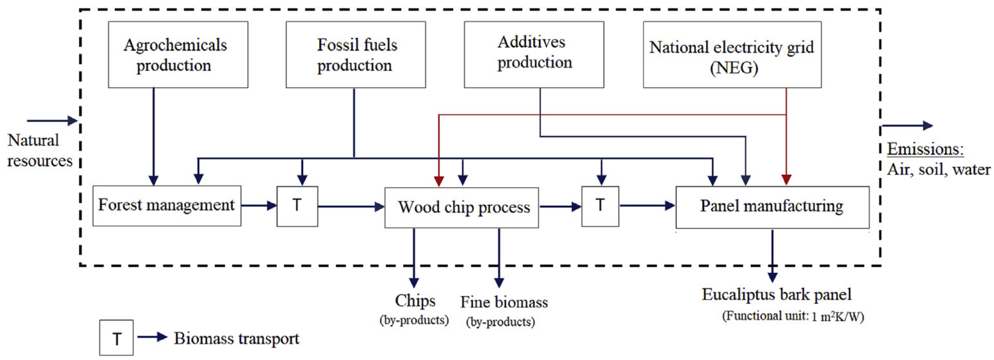


**Fig. 1.** System boundaries for the cradle-to-gate for production of eucalyptus bark panel.

consumption (0.039 lts) per $m^3$ of chips bark free ($m^3$ssc) were gathered according to primary data available in National Environmental Declaration System (SEIA, 2018). The inventory data for wood chips is provided in Table S3 of Supplementary Information.

*2.1.2.3. Panel manufacturing.* Pilot-scale panel manufacture plant installed at the Technology Development Unit of the University of Concepción was taken as reference for the estimation of yields, resources consumption and emissions.

This plant involves the pre-treatment stage, milling, blending and panel consolidation. Firstly, the Eucalyptus barks are crushed and then dried to 15–20% (dry basis) moisture content. After that, the barks enter into a second milling stage for obtaining fibers with a variable length (1–30 mm) and thickness of (0.2–0.5 mm). Then synthetic fibers (bicofibers - polyethylene and polypropylene) are added to bark-derived fibbers at a ratio of 4 wt percentage (%wt./wt.) and then, flame retardant (1 %wt./wt.) and antifungal (1 %wt./wt.) are added to the mixture. Finally, the blend is sent to panel consolidation, which is carried out through a low-pressure steam injection process.

The steam demand in the dryer and during pressing are supplied through a natural gas burner, and the electricity demand is fulfilled by the National electricity matrix. Thus, primary emissions are related to natural gas combustion and to the biomass waste generated during milling, sieving and sizing stages. More detail of inventory data for panel manufacturing is provided in Supplementary Material (Table S4).

The mains physical characteristics of the panels (density, weight, thermal conductivity) were measured and depicted in Table 1.

*2.1.2.4. Biomass transportation.* The transportation of eucalyptus logs and barks is considered to be by trucks of 16–32 tons of capacity. Firstly, the logs are transported from forest plantation to wood chips plant, where the eucalyptus barks are separated. After that, the Eucalyptus barks are transported to the panel manufacturing facility.

The average distances traveled by trucks were limited to Biobío and Ñuble regional boundaries and, were established based on the actual location of forest plantations, wood chipping stations, and the pilot-scale panel manufacturing plant. The inventory data for transportation was gathered from the Ecoinvent database, and the traveled distances were estimated using the information provided by Google Earth. According to Fig. 2, we considered an average distance of 130 km between the wood chipping station and panel manufacturing facility, specifically for logs transportation, an average distance of 50 km was chosen. Furthermore, the transports associated with agrochemicals, fuels, and additives were also taken into account. More information related to providers and distances considered for each agrochemical, fuels, and additives is available in Supplementary Material (Table S1).

### 2.1.3. Allocation principles

The environmental impacts associated with a multi-outputs process should be shared between all products (Ekvall and Finnveden, 2001). In this study, the biomass generated in forest management such as leaves, branches and stumps has not been considered and estimated for the harvesting stage (Morales et al., 2015). Thus, the allocation rules were not required for this stage.

The allocation principles are required for the wood chipping process. The chips are the main product obtained in that process, being eucalyptus bark and sawdust the by-products. The environmental burdens have been distributed using mass criteria. According to this principle, the chips, eucalyptus bark, and sawdust represent 84%, 11% and 5%, respectively.

## 2.2. Life cycle inventory

Inventory data of the forest management and wood chipping process were extracted on-site for industries existing in the Biobío region and complemented with bibliographic sources (Morales et al., 2015; SEIA, 2018). The primary data corresponds to fossil fuel consumption, herbicides, fertilizer, seedling, biomass productivity, electricity consumption, and chips yield. The air and water

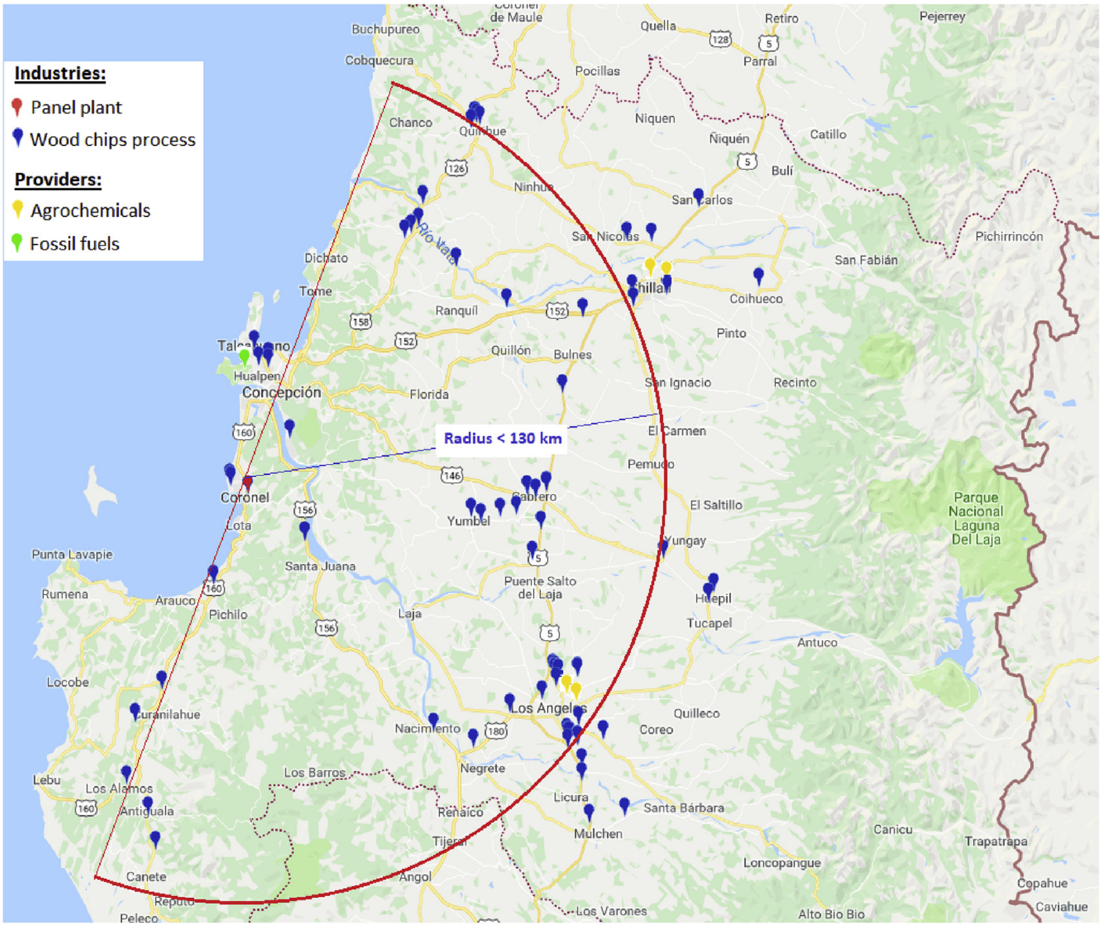


**Fig. 2.** Location of wood chip process, panel manufacturing, and principals agrochemicals and fossil fuel providers for Biobío and Ñuble regions (INFOR, 2016).

emissions associated with the fertilization stage is completed using emission factors reported in the literature (EPA, 1998; Morales et al., 2015). In the case of panel manufacturing, the primary data was measured in-situ from pilot-scale panel plant described in section 2.2.3.

The secondary data associated to the production of herbicides, fertilizers, additives and fossil fuel consumed in the silviculture, transport and panel manufacturing were retrieved from the Ecoinvent v2.1 database (Swiss Centre for Life Cycle Inventories., 2010). Furthermore, electricity generation was modeled using power plants datasets available in Ecoinvent, taking as base the national electricity matrix configuration (CNE, 2018). This database was also used for obtaining the air emissions derived from diesel combustion in forest machinery (tractors, forwarders, and skidders) and transport stage (biomass, additives, agrochemicals, etc.). The life cycle inventories for each stage are specified in Supplementary Materials.

### 2.3. Life cycle impacts assessment

The environmental impacts are determined using CML-IA baseline vs. 3.02, world 2000 method, which is oriented to midpoint life cycle assessment approach. This model involves the following impact categories: abiotic depletion, fossil fuel depletion, global warming (GWP100), ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication. The SimaPro v 8.1 software was used for modeling all life cycle processes (Pré, 2008).

## 3. Results and discussion

### 3.1. Environmental analysis

The comparison of environmental impacts derived from the manufacturing of eucalyptus bark panels with different bulk densities is depicted in Table 2. The impacts categories were referred to the functional unit defined in Eq. (1).

According to these results, the panel with a density of 100 kg/m$^3$ showed the highest impacts for all the categories when compared to the rest of panels, representing an increase of 72%, 46% and 22% for densities of 25, 50 and 75 kg/m$^3$, respectively. This performance is related to the higher amount of panel mass (f.u) required to guarantee the same thermal resistance, what translates into higher resources consumption and pollutants emitted along the biomaterial life cycle. In this case, the amounts needed for the density of 100 kg/m$^3$ were approximately 4.4, 2.1 and 1.4 times higher than the mass required for densities of 25, 50 and 75 kg/m$^3$, respectively.

The thermal conductivity is a common property used to characterize the insulation capacity of a material; thus higher conductivity means that the material will be less attractive for insulation. In fact, thermal conductivity linearly correlates to the board density (Zhou et al., 2010). Accordingly, results in Table 1 suggest that the panels with lower densities (corresponding to 0.045 W/mK) could be a potential alternative for reducing impacts, due to the use of less bark for producing the same insulation effect. Considering that the

**Table 2**
Environmental profile of manufacturer of the eucalyptus bark panel referred to f.u. (kg).

| Impact categories | Unit | 25 kg/m$^3$ | 50 kg/m$^3$ | 75 kg/m$^3$ | 100 kg/m$^3$ |
|---|---|---|---|---|---|
| Abiotic depletion | kg $Sb_{eq}$/f.u | 1.90E-06 | 3.90E-06 | 6.09E-06 | 8.46E-06 |
| Abiotic depletion (fossil fuels) | MJ/f.u | 16.2 | 33.6 | 52.5 | 72.3 |
| Acidification | kg $SO_{2eq}$/f.u | 9.49E-03 | 1.94E-02 | 3.03E-02 | 4.17E-02 |
| Eutrophication | kg $PO_{4eq}$/f.u | 5.97E-03 | 1.22E-02 | 1.91E-02 | 2.61E-02 |
| Global warming potential ($GWP_{100}$) | kg $CO_{2eq}$/f.u | 1.35 | 2.77 | 4.32 | 5.92 |
| Ozone layer depletion | kg CFC-$11_{eq}$/f.u | 1.42E-07 | 2.90E-07 | 4.51E-07 | 6.22E-07 |
| Human toxicity | kg 1,4-$DCB_{eq}$/f.u | 1.13E-01 | 4.91E-01 | 7.67E-01 | 1.09 |
| Fresh water ecotoxicity | kg 1,4-$DCB_{eq}$/f.u | 9.13E-02 | 1.88E-01 | 2.91E-01 | 4.08E-01 |
| Marine aquatic ecotoxicity | kg 1,4-$DCB_{eq}$/f.u | 2.63E-01 | 5.41E-01 | 8.40E-01 | 11.80E-01 |
| Terrestrial ecotoxicity | kg 1,4-$DCB_{eq}$/f.u | 1.01E-03 | 2.13E-03 | 3.29E-03 | 4.62E-03 |
| Photochemical oxidation | kg $C_2H_{4eq}$/f.u | 2.39E-04 | 4.91E-04 | 7.66E-04 | 1.07E-03 |

forest and industry (wood chipping process and panel manufacturing) yields were considered the same for all the studied alternatives; we attributed the differences observed in the environmental profiles to differences between panel densities and thermal conductivities.

A detailed profile describing the contribution of each stage of the manufacturing of the Eucalyptus bark panels to the life cycle impacts, is provided in Fig. 3. The contribution by stages for all studied panel show the same environmental patterns, due to the forest yield, the efficiency of wood chipping process and eucalyptus bark panel, as well as, the distances traveled for transport stages are considered the same for all types of panels. Accordingly, in the upcoming sections, the discussion relies on the panels of 25 kg/m$^3$.

*Abiotic depletion:* the stages with higher contributions on this impact category were forest management (51%), followed by transport (30%) and panel manufacturing (18%). The relevant contribution of harvesting is mainly associated with the diesel consumed by the forest machinery. Moreover, the agrochemicals (fertilizer and pesticides) required during forest management also implies an important contribution to this category. In the case of transport, the high fossil fuel demand and large traveled distances for biomass are the causes of abiotic depletion. The eucalyptus bark panels manufacture also depicted significant contribution to abiotic depletion, due to the environmental charges associated to the additives (synthetic fibers, antifungal, and flame retardant) and fossil fuel (natural gas) demanded by this process.

*Fossil fuel depletion* is related to fossil fuel consumption along the whole panel life cycle. The stage of panel manufacture shown the highest impacts, representing 63% of the total for this category. One of the causes for this high contribution is the natural gas consumption by the steam generation system to fulfil the heat demand during panel production. Indeed, the steam demand (16.2 MJ/f.u) implies a 17% of total environmental charge for this category. In order to reduce the impact produced by fossil fuel consumption, the use of biomass as fuels for a steam generation could be an attractive solution.

Furthermore, the synthetic fibers (polypropylene/polyethylene) used in the panel also involved a significant impact, which contributed to 13% of the total consumed non-renewable fuels. These results are in agreement with that previously reported by

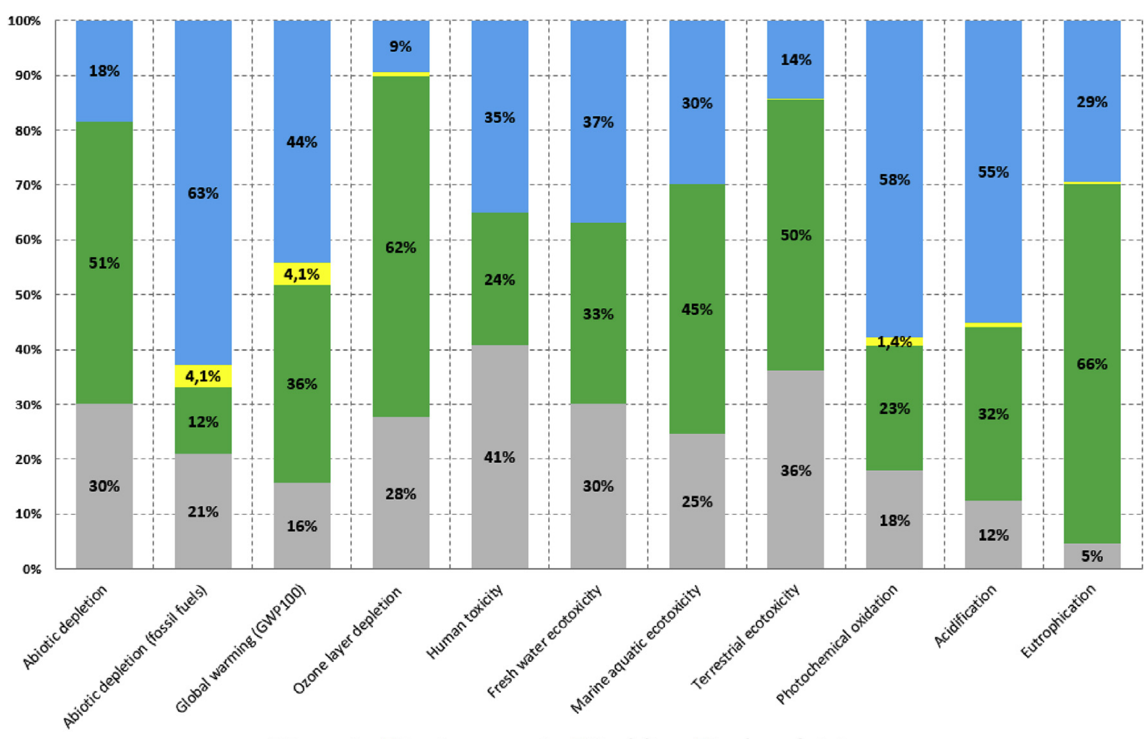


**Fig. 3.** Contribution of each life cycle stage to total impacts for eucalyptus bark panel of 25 kg/m$^3$. CML-IA 2 baseline 2000 v3.02/Word 2000.

(Ardente et al., 2008), who found that polyester synthetic fibers represented nearly 35% of the total energy required in kenaf panel. The differences in terms of contributions obtained here with the findings of (Ardente et al., 2008) could be related with the amount of synthetic fibers used in the manufacture of the kenaf panel (0.15 kg polyester fibers/kg panel), demanding three-times higher quantity of fibers than for eucalyptus bark panels (0.042 kg/kg panel).

On the other hand, the transport (21%) and forest management (12%) accounted for 47% of total fossil fuel depletion impact. This impact is mainly caused by the diesel used in the biomass transport from forestry plantations to the industry, as well as, due to the fuels consumed by forest machinery.

*Global warming potential* is directly correlated with non-renewable energy demand, where the fossil fuels are the main precursors of greenhouse gases emission ($CO_2$, $CH_4$ and $N_2O$), thereby on global warming potential. In this study, the more representative stages were the manufacture of the panel (44%), forest management (36%) and transport (16%). The production of synthetic fibers and natural gas combustion are the most relevant contributors for panel manufacturing. Meanwhile, the forest management contribution is mainly associated to the GHG emitted by forestry machinery and the $N_2O$ emitted by the application of nitrogen-based fertilizers. Besides, the transport is correlated to the large distances traveled by the wood trunks to panel manufacturing (130 km) facilities.

As discussed previously, the use of biomass as fuel for a steam generation does not only constitute an effective alternative for reduction of the fossil fuel depletion category, also for the GHG mitigations. The impact on this category could be reduced by 36% if such a fuel replacement is included. Moreover, the nitrogen emissions derived from nitrogen fertilizers application in the crop establishment and harvesting could be avoided by the use of organic fertilizers (e.g. biochar).

*Ozone layer depletion: the* major contribution of this indicator was found for forest management, accounting for 62% of the total impacts. This behavior is closely related to the use of pesticides and its corresponding air, soil and water emissions. Furthermore, biomass transport also presents a significant impact on this category, representing a 28%. Therefore, fossil fuel consumption and agrochemicals application impact negatively on ozone layer depletion. These results are in concordance with that reported by (Casas-Ledón et al., 2019; Morrison and Golden, 2017), who remarked that the diesel consumed in biomass transportation and herbicides applications resulted in a larger Ozone Depletion Potential for biomass-energy routes.

*Acidification potential* is caused by gases emissions such as $SO_2$, $NH_3$ and $NO_X$. In this study, the sulfur content of natural gas was negligible; accordingly, negligible $SO_2$ was obtained during panel manufacturing. Therefore, the NOx emission produced by the steam generation constitute the main precursors for the acidification impacts, contributing to 55% of the total. Meanwhile, the $SO_2$ also plays a significant impact on this category for transport and forest management stages, which is dependent on sulfur content in diesel and efficiency in its combustion. The forest management (32%) was the second major contributor to acidification potential, followed by biomass transport (12%).

*Eutrophication potential:* Forestry stage showed higher impacts on eutrophication potential, accounting for 66% of the total. This significant contribution is related to nitrogen and sulfur oxides emissions coming from diesel combustion in forestry machinery, as well as, the nitrate and phosphate emissions derived from uses of fertilizer and pesticides (See Supp. Material Table S2). In this sense, several studies have been highlighted the significant impact of the fertilization process of the forest management on eutrophication potential (Casas-Ledón et al., 2019; Cherubini, 2010; Huang et al., 2013). Besides, the manufacture of eucalyptus bark panel also has a significant impact on eutrophication, due to natural gas demand and synthetic fibers production.

*Photochemical oxidation.* As shown in Fig. 3, panel manufacturing accounted for the most significant effect in this category, which resulted from $NO_X$, $CH_4$ and CO emissions. These emissions comes primarily from the production and combustion of natural gas, as well as, from synthetic fibers and flame retardant production processes; followed by biomass harvest (23%) and transport (18%). For forestry harvest, the air emissions from machinery are the main contributors to this impact category. Meanwhile, for transport stage, this impact was mainly related to the extraction and combustion of diesel.

*Ecotoxicities.* The forestry, transport and panel manufacturing are the most relevant processes affecting the ecotoxicities, being more significant the contribution of forest management for marine (50%) and terrestrial (45%) ecotoxicities. This performance is related to the production and application of pesticides and fertilizers. Besides, the manufacture of panel and transport showed higher impacts on freshwater (37%) and human (41%) toxicities, respectively. The production of synthetic fibers and additives (flame retardant and antifungal) used in the manufacture of eucalyptus bark panel are the reasons of significant impacts on freshwater toxicity; meanwhile, the relevance of transport is associated to extraction and uses of diesel.

According to the previous discussion, the manufacture of eucalyptus bark panels constitutes a crucial stage in the bio-insulator supply chain, associated mainly to additive types and fossil fuel consumption. However, the substitution of energy sources and synthetic material by more sustainable ones, could tailor the environmental profile of panels manufacturing.

Additionally, forest management showed significant impacts in many categories (abiotic depletion, ozone layer depletion, marine and terrestrial ecotoxicities, and eutrophication), which are strictly dependent on forestry yield and intensive management. At the same time, biomass transportation plays an essential role in the environmental profile of the process. The relevance of biomass transportation is still a challenge for bio-composite and bio-energy routes due to the physical nature of biomass, its moisture content, distances from the biomass conversion system to the field, and modes of transportation (Sansaniwal et al., 2017). Specifically, in our study, the large distances for eucalyptus bark transportation (130 km) from wood chipping process to the panel manufacturing facility is the main reason for the high contributions of this stage. However, these contributions could be significantly reduced if the panel manufacturing facility is integrated into the wood chipping process.

#### *3.1.1. Remarks on the assumptions made for the LCA analysis*

In this study, the inventories associated with the production of herbicides, fertilizers, additives and fossil fuel consumed in the silviculture, transport and panel manufacturing (background system) were gathered from ecoinvent database. This database is recognized and accepted in the LCI field due to its completeness and representativeness of the data for a wide spectrum of processes and scenarios. Nevertheless, there are some uncertainties related to the assumption made for local production systems (forest yield, biomass transport distances) and to the LCA methodology (allocation rules and system boundary). In this sense, main assumptions were related to the distances for biomass hauling from forest to primary processing stations and from there to panels manufacturing facility. Indeed, this is the main reason of the high impacts estimated for the transport stage. The average distances traveled were limited to Biobío and Ñuble regional boundaries and, were established based on the actual location of forest plantations, wood chipping stations, and the pilot-scale panel manufacturing plant. However, the biomass distances traveled could be higher than that used here, implying higher impacts due to fossil fuel production and consumption. According to the results obtained here, the optimization of biomass transportation distance must be carried out to decide the plant location.

Moreover, the significant contribution of the silviculture stage was associated mainly with the fertilizer dose, which was strongly correlated to the forest yield. In consequence, the contribution of silviculture stage could be overestimating the environmental profile, specifically for abiotic depletion, ozone layer depletion, ecotoxicities, acidification, and eutrophication categories. In this case, the forest yield was assumed 18.8 $m^3$/ha.yr (Morales et al., 2015), which is lower than that reported by (Corvalan Vera and Hernandez Palma, 2012) (28 $m^3$/ha.yr).

Regarding allocation principles, significant differences could be obtained in the environmental profile when the economic allocation is applied instead of material allocation. The material allocation implies that the eucalyptus bark receives 11% of all feedstock requirements in the wood chipping process. This picture changes when the economic allocation is applied; for which the eucalyptus bark will receive 6% of all resources demand. This lower contribution also implies lower resource demand (agrochemicals, fuels, etc.) for silviculture and transport stages; thus leading to a major environmental benefit for economic-based allocation.

On the other hand, the operational stage constitutes the principal driver in carbon emissions and energy consumption (Biswas, 2014; Li et al., 2017) in building life cycle assessment. The exclusion of installation and maintenance of the eucalyptus bark panels, as well as, the disposal at the end of their life (grave) into system boundaries could carry out an underestimation of the environmental burdens. In addition, the different alternatives for the disposal (landfilling disposal, incineration reusability and recyclability) of panels could also bring significant differences in the results of the impact categories considered here. Besides, the durability of panel could bring changes in the environmental impacts of the building operation stage. Nowadays, this eucalyptus bark panel is in developing stage, where the physical and mechanical properties are being optimized. For that reason, we do not have an exact estimation on the durability of the panel. Nevertheless, we expect that de durability will be similar to other panel manufactured with natural fibers (kenaf, hemp). In this sense, several studies have considered the panel durability as the same life time of buildings, which could be considered between 30 and 50 years (Ardente et al., 2008; Senga et al., 2017).

### 3.2. Comparative analysis of different thermal insulation panels

Biomaterials are recognized as renewable alternatives for sustainable buildings, contributing to climate change mitigation and to the reduction of embodied energy, in comparison with non-renewable traditional insulation materials based on synthetic fibers. In this sense, the global warming impact and energy consumption have been the categories widely used to compare different bio-composites routes from an environmental point of view (Ardente et al., 2008; Buratti et al., 2018; Ricciardi et al., 2014; Schiavoni et al., 2016). Accordingly, the equivalent carbon emissions (kg$CO_{2eq}$/f.u) and embodied energy (MJ/f.u) from the eucalyptus bark panels were compared to other insulation materials reported in the literature (Table 3).

The proposed material (eucalyptus bark) shown competitive thermal conductivities (0.045–0.049 W/m.K) in comparison with the rest of the biomaterials. Nevertheless, the traditional insulation fibers (expanded polyurethane, polystyrene, glass fibers) present better thermal properties than natural-based ones, but with a higher embodied energy and carbon emissions.

Regarding total carbon emissions and embodied energy per f.u, the values differ significantly between materials, taking values ranging between 1.1 and 10 kg$CO_{2eq}$/f.u and 16.2–229 MJ/f.u. In general, the environmental performance of thermal insulation material coming from natural fibers (hemp, kenaf, rice husk, eucalyptus bark) shows lower energy demand (16.2–72.3 MJ/f.u) and carbon emissions (1.1–5.9 kg$CO_{2eq}$/f.u) than traditional materials (50–229 MJ/f.u and 2.5–10 kg$CO_{2eq}$/f.u). In this sense, the higher energy consumption and carbon emissions were depicted for glass wool (229 MJ/f.u and 9.8 kg$CO_{2eq}$/f.u), glass fibers (140 MJ/f.u and 10 kg$CO_{2eq}$/f.u), expanded polyurethane (125 MJ/f.u and 5.1 kg$CO_{2eq}$/f.u) and expanded polystyrene (130 MJ/f.u and 5.0 kg$CO_{2eq}$/f.u). These results corroborate that the source of material plays an important role in the environmental profile.

A rational conclusion could be that materials produced from non-renewable sources will be more impacting than natural-derived ones, particularly due to equivalent carbon emissions. However (Schiavoni et al., 2016), demonstrated that low energy demand and, consequently, low carbon emissions characterized some traditional materials. Indeed, stone wool and recycled PET presents lower embodied energy and global warming potential than kenaf fiber, cellulose, and Eucalyptus bark. Besides, the environmental impacts for each material are strongly influenced by modeling assumptions and input parameters. These uncertainties are mainly related to system boundaries, technology efficiency, completeness and representativeness of the input data.

Making a comparison between the eucalyptus bark panels with other materials coming from natural fibers, the energy consumption is in the same order of magnitude to that previously reported. Specifically, the eucalyptus bark panels with a density lower than 50 kg/$m^3$ depicted lower energy demand (16.2–33.6 MJ/f.u.) than kenaf fibers (42–59.4 MJ/f.u.), jute fibers (105 MJ/f.u.) and rice husk (47 MJ/f.u.), respectively. This performance is closely related to the amounts of material required to fulfill the same thermal resistance ($R = 1$ $m^2$K/W), which is dependent on thermal properties and mass densities of panels. The higher mass density and thermal conductivity higher the requirement of material. Accordingly, the panel coming from jute fibers (100 kg/$m^3$ and 0.050 W/mK) and rice husk (170 kg/$m^3$ and 0.070 W/mK) depicted higher mass densities and thermal conductivities than eucalyptus bark (50 kg/$m^3$ and 0.048 W/mK), implying approximately 2 and 5 higher demand of material. Furthermore, the increment of density in eucalyptus bark panels produces a significant increase of embodied energy in comparison with the majority of panels from natural fibers (cellulose, kenaf, hemp and rice husk). Particularly for densities of 100 kg/$m^3$ (72.3 MJ/f.u.) the energy demand depicted an increment of 60%, 22% and 72% concerning to rice husk, kenaf and hemp fibers, respectively. Meanwhile, the increase was approximately three times higher than the cellulose.

From an equivalent carbon emissions point of view, similar patterns as for the embodied energy category were found. Eucalyptus bark panels with densities below 50 kg/$m^3$ depicted comparative carbon emission as the rest of natural fibers. In contrast, the panels with densities above 75 kg/$m^3$ shown the highest emissions.

The eucalyptus bark panel with densities above 50 kg/$m^3$ shown lower emissions (1.4–2.8 kg $CO_{2eq}$/f.u.) in comparison with rice husk (1.9 kg $CO_{2eq}$/f.u), kenaf (1.1–3.2 kg $CO_{2eq}$/f.u.), hemp (1.13 kg $CO_{2eq}$/f.u.), cellulose (1.2–3.6 $CO_{2eq}$/f.u) and jute fibers (2.8 kg $CO_{2eq}$/f.u).

The significant differences in this study concerning the rice husk panels (Buratti et al., 2018), could be related to the lower amount of eucalyptus bark needed to fulfill the same thermal resistance (ten

**Table 3**
Comparative analysis of typical thermal insulation materials with Eucalyptus bark fibers.

| Materials | ρ (kg/m$^3$) | Λ (W/mK) | f.u. (kg) | Embodied energy (MJ/f.u) | kgCO$_{2eq}$/f.u | References |
|---|---|---|---|---|---|---|
| Expanded polyurethane | 30 | 0.030 | 0.90 | 125 | 5.1 | Ricciardi et al. (2014) |
| Expanded polystyrene | 20 | 0.040 | 0.8 | 130 | 5.0 | Ricciardi et al. (2014) |
| Recycled PET | 40 | 0.037 | 1.48 | 21.1 | 3.12 | Schiavoni et al. (2016) |
| Glass wool | 160 | 0.050 | 8.0 | 229 | 9.8 | Ricciardi et al. (2014) |
| Stone wool | 30 | 0.040 | 1.2 | 50 | 2.5 | Ricciardi et al. (2014) |
| Glass fibers | 20 | 0.040 | 0.80 | 140 | 10.0 | Ricciardi et al. (2014) |
| Cellulose | 60 | 0.039 | 2.34 | 19.4 | 1.20 | Ricciardi et al. (2014) |
| | 50 | 0.040 | 2.00 | 21 | 3.66 | Schiavoni et al. (2016) |
| Hemp | 50 | 0.038 | 1.9 | 42 | 1.13 | (Ricciardi et al., 2014; Schiavoni et al., 2016) |
| Kenaf fibers | 40 | 0.038 | 1.52 | 59.4 | 3.2 | Ardente et al. (2008) |
| | 50 | 0.038 | 1.90 | 42.3 | 1.1 | Schiavoni et al. (2016) |
| Jute fibers | 100 | 0.050 | 5.0 | 105 | 2.8 | Schiavoni et al. (2016) |
| Rice husk | 170 | 0.070 | 11.9 | 45 | 1.9 | Buratti et al. (2018) |
| **Eucalyptus bark fibers** | **25** | **0.045** | **1.13** | **16.2** | **1.4** | **This work** |
| | **50** | **0.046** | **2.3** | **33.6** | **2.8** | |
| | **75** | **0.048** | **3.6** | **52.6** | **4.3** | |
| | **100** | **0.049** | **4.9** | **72.3** | **5.9** | |

times lower than rice's husk panel), specifically for density of 25 kg/m$^3$. The mass requirement for eucalyptus bark with a density below 50 kg/m$^3$ (2.3–4.9 kg) still being lower than rice husk (11.9 kg); nevertheless the equivalent carbon emissions are higher. This high indicator can be explained by the high energy (fossil fuel and electricity) demand for producing agrochemicals, and additives used in the forestry management and eucalyptus bark panels manufacturing. Therefore, the crops harvest and panel manufacturing plays an essential role in environmental impacts, which can vary significantly depending on crop characteristic and the technology used for panel manufacturing (bonding molding, hot-pressing molding, injection molding, etc) (Liu et al., 2017).

On the other side, the significant differences in carbon emissions obtained here in comparison with kenaf fibers are associated with the natural fiber harvesting and panel production method, as well as, with the system boundaries assumptions made for life cycle assessment. According to the latter aspect, the higher carbon emissions of the reference case (Ardente et al., 2008), are related to the inclusion of panel disposal (incineration process) into system boundaries, which represented 23% of total carbon due to the combustion of polyester. However, different final disposal alternatives (incineration, recycling, landfill, etc) could establish differences in terms of carbon emissions compared to those reported here. Furthermore, an increment of equivalent carbon emissions is expected when the operational and final disposal phases are considered in the whole value chain of material (Ardente et al., 2008). reported the carbon emissions for kenaf fibers panels production considering cradle to grave as system boundaries and they found higher values than those estimated by (Schiavoni et al., 2016), who also assessed the life cycle of kenaf fibers panel but considering cradle to gate boundary.

The higher global warming impact category found here as compared to that reported by (Schiavoni et al., 2016), could be explained by the higher requirement of fossil fuel, fertilizer, synthetic fibers in the harvesting and panel manufacturing phases. The fertilizer and fossil fuel consumption for the eucalyptus harvesting stage represents twice and fifteen times higher than for kenaf panels. Also, the synthetic fibers consumption for manufacturing the eucalyptus bark panels is twice higher than for kenaf material. Those results reflect the relevance of the harvesting method (productivity) and manufacturing technology (efficiency) on equivalent carbon emissions.

Finally, the results could be contradictory when assessing the correlation between embodied energy and carbon emissions. Accordingly, we expected that higher energy consumption also implies higher carbon emissions; however, there is not a clear correlation between both indicators. This performance could be associated to total embodied energy also involves renewable and non-renewable energy sources, being the non-renewable energy sources the primary precursor of equivalent carbon emissions. In consequence, higher energy consumption does not necessarily implies higher carbon emissions. This pattern can be corroborated for jute fibers, which depicted highest embodied energy (105 MJ/f.u) in comparison with the rest on natural materials (hemp, kenaf fibers, rice husk, eucalyptus bark). Meanwhile, the carbon emissions values are lower than kenaf fibers (3.2 kg kgCO$_{2eq}$/f.u) and eucalyptus bark for density above 75 kg/m$^3$ (4.3–5.9 kgCO$_{2eq}$/f.u). A similar pattern is depicted for synthetic materials (glass wool, glass fiber, expanded polyurethane and polystyrene). For eucalyptus bark panels, a proportional correlation between carbon emissions and energy consumption is found, which can be associated to the assumptions used for life cycle assessment.

## 4. Conclusions

This paper provides detailed results that enables an assessment of the environmental performance for the life cycle of eucalyptus bark-based insulating panels. The panels with the lowest density (25 kg/m$^3$) shown better environmental profile, mainly due to their lower conductivity and reduced requirements of mass. Moreover, the panels with a density below 50 kg/m$^3$ depicted the lower impacts on embodied energies and carbon emissions categories than traditional insulation materials (glass fibers, glass wool, expanded polyurethane and expanded polystyrene) and non-conventional materials coming from natural fibers (kenaf, jute and rice husk). Therefore, the eucalyptus barks as natural fiber, could be a promising feedstock for producing thermal insulating panels with potential applications in the building sector.

The manufacturing of eucalyptus bark panels constitutes a crucial stage in the material life cycle, mainly due to the use of synthetic fibers for composite formulation and natural gas for process energy supply. Moreover, forest management and biomass transportation depicted a significant contribution to the environmental profile, due to forestry intensive management and considerable distance traveled, respectively.

## 5. Future work

There are still several unsolved questions regarding the use of eucalyptus fibers for preparing insulation materials. For example there is no data or a detailed forecasting about the usable life for these panels. Indeed, it is expected that de durability could be similar to other natural fibers-based panels (e.g., kenaf, hemp) but a study on that is still undue.

Regarding the disposal of panels at their end-of-life (grave), several alternatives could be considered, for example the landfilling disposal (with energy recovery), reusability and recyclability, as well as incineration with energy recovery (Arrigoni et al., 2017; Asdrubali et al., 2015; Quintana et al., 2018; Schiavoni et al., 2016). The incineration with energy recovery could be attractive due to the high organic content of panels. However, special attention should be paid to the composition of the combustion gases mainly to those associated to the combustion of chemicals and additives used during panel manufacturing (impregnating substances, glues and adhesives). Besides, the reusability and recyclability could be limited by the effective separation of the panels from other buildings materials during the dismantling phase.

## Credit author statement

Yannay Casas-Ledón: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision. Karen Daza Salgado: Investigation. Juan Cea: Resources: Investigation. Luis E. Arteaga-Pérez: Writing – review & editing. Cecilia Fuentealba: Conceptualization, Investigation, Resources, Supervision, Project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

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